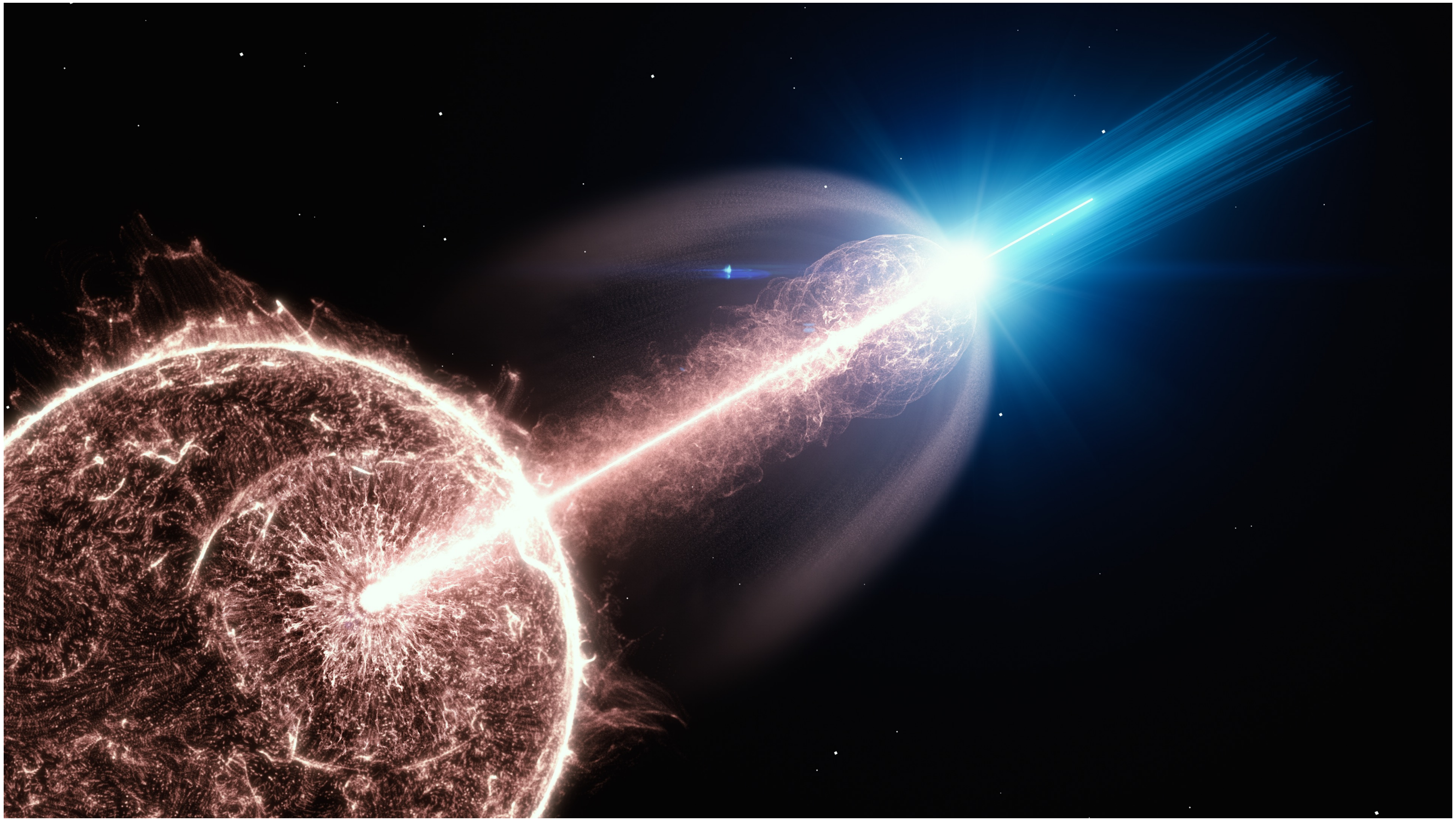
# New Observations Probing Particle Acceleration in GRB Outflows



THESE ARE EXCITING TIMES!

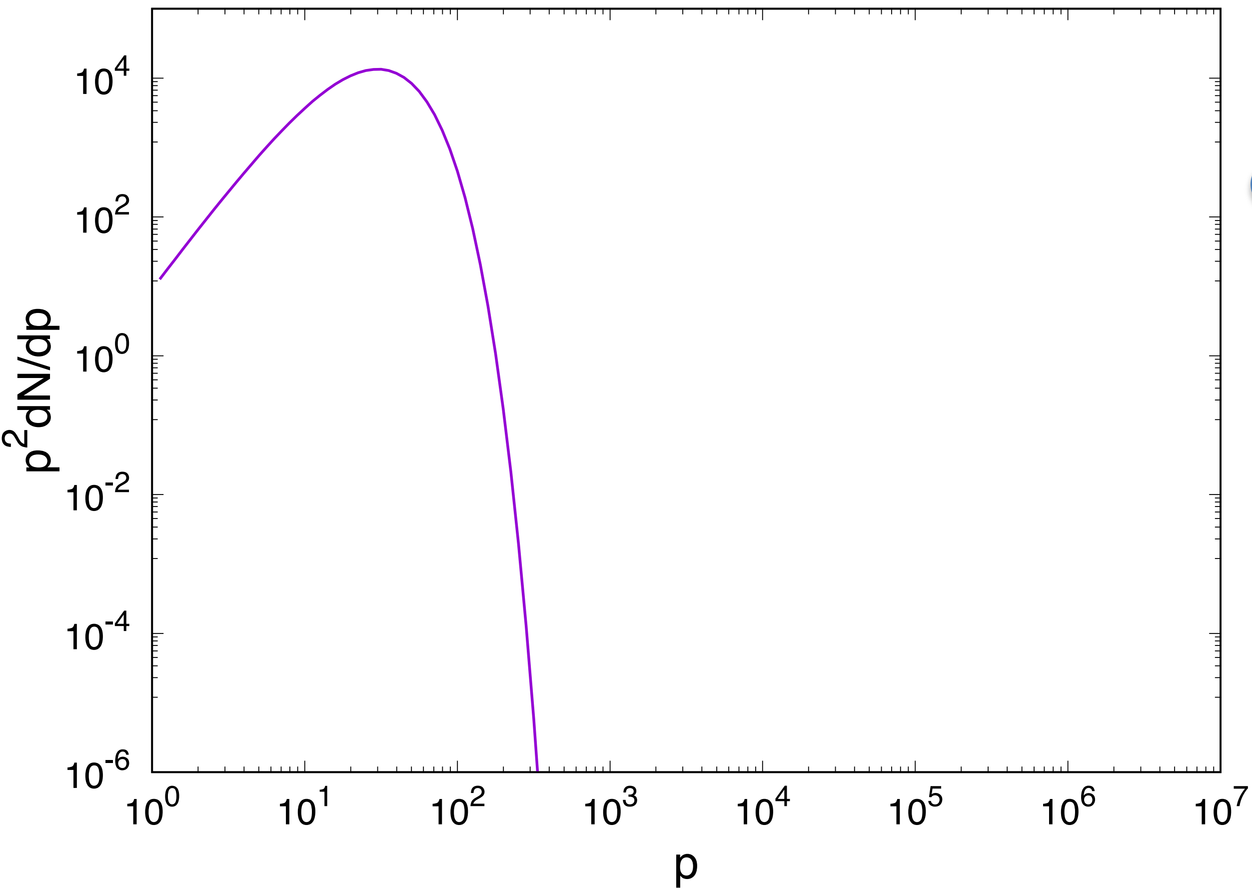
DESY.

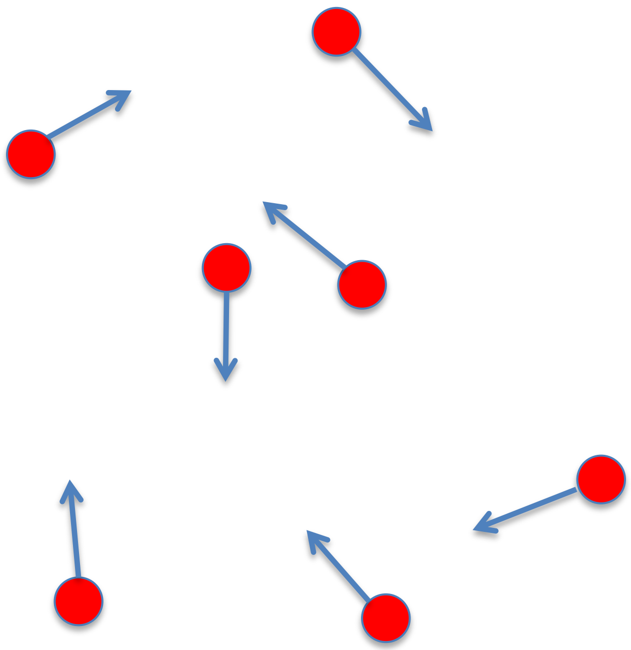
Andrew Taylor

# Why Do Non-Thermal Particles Exist?

WARNING- EXISTENCE QUESTIONS ARE HARD!

# Thermal Particles



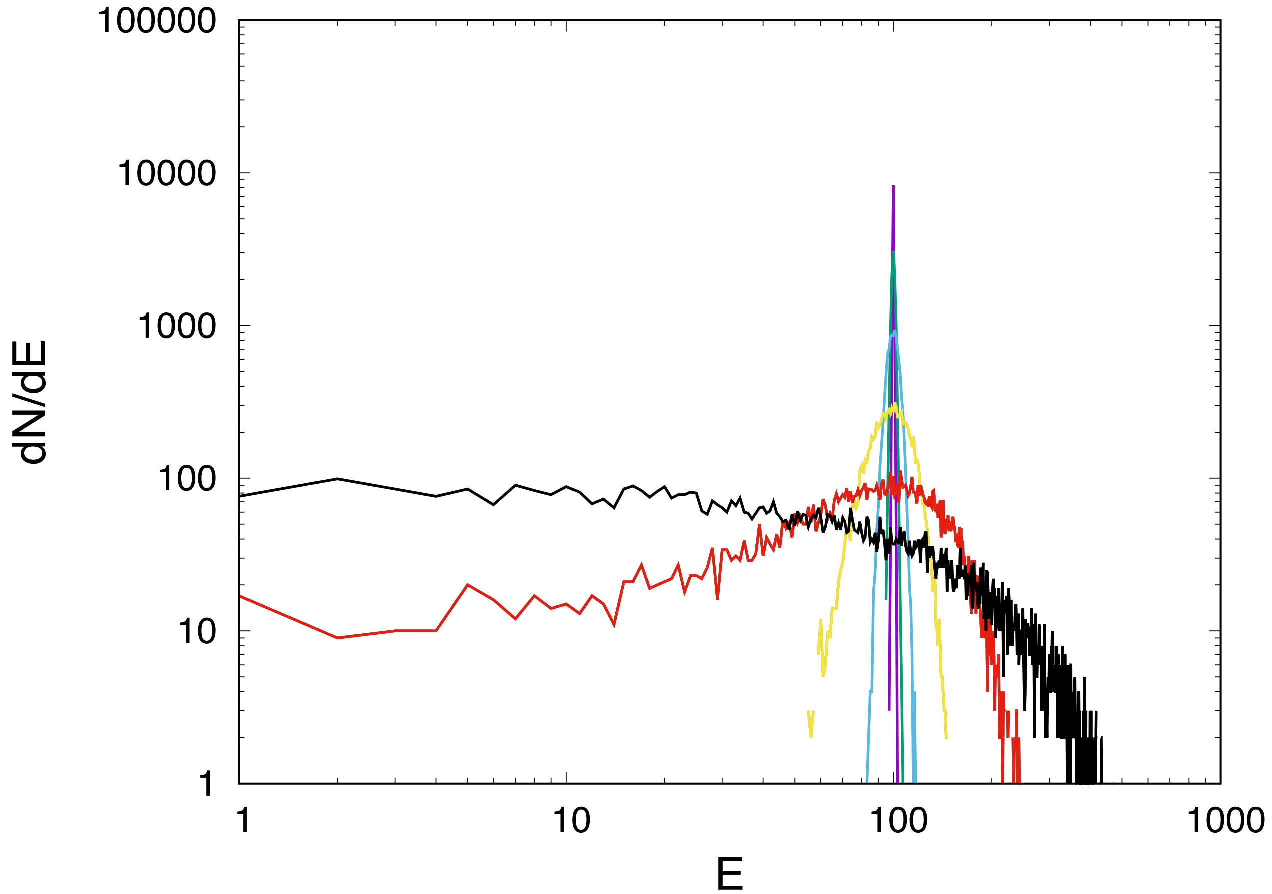
# Why the Exponential Cutoff?

Ensemble of particles exchanging energies:

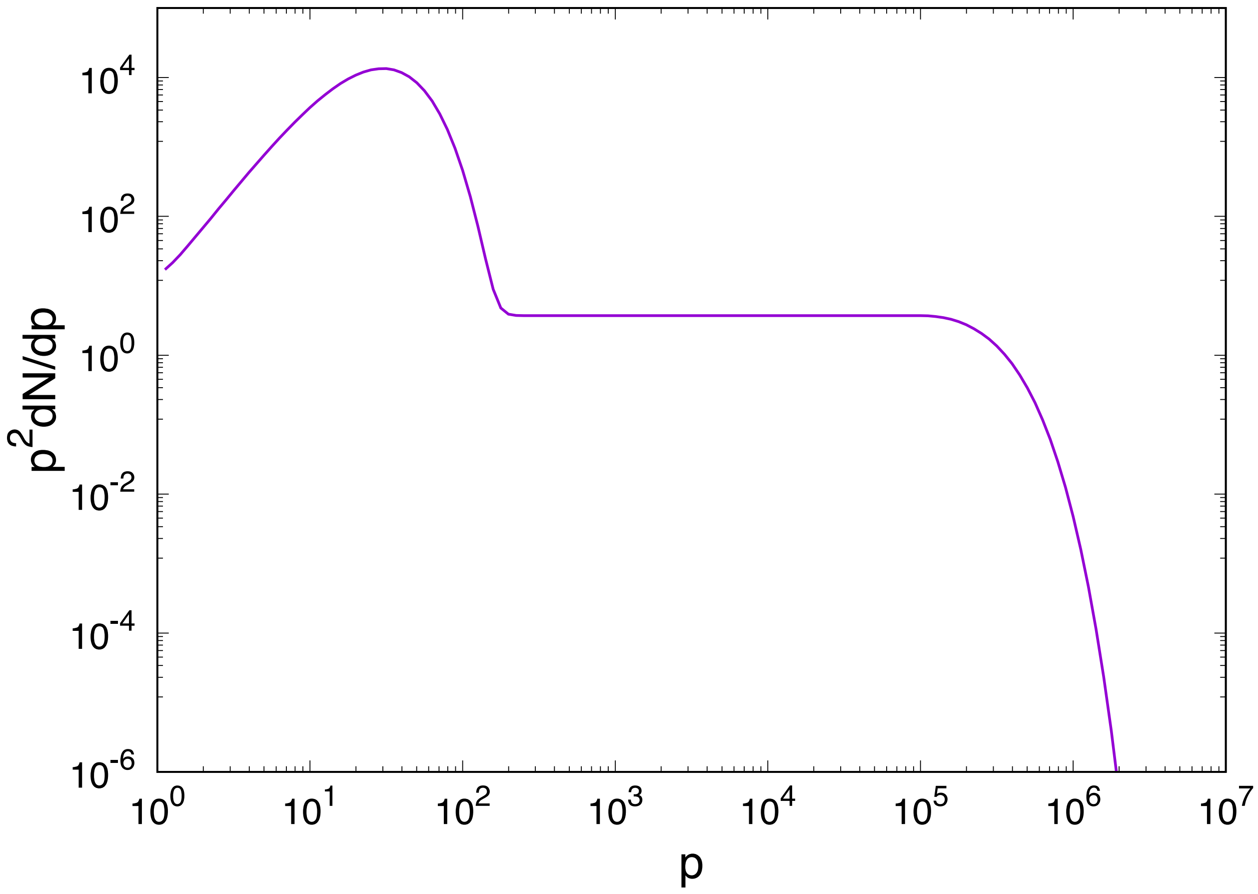
| $E_1$ | $E_2$ | $E_3$ | $E_4$ | $E_5$ | $E_6$ |
|---|---|---|---|---|---|
| 100 | 100 | 100 | 100 | 100 | 100 |
| 101 | 99 | 100 | 100 | 100 | 100 |
| 101 | 99 | 100 | 100 | 99 | 101 |
| 100 | 99 | 101 | 100 | 99 | 101 |
| 100 | 98 | 101 | 100 | 99 | 102 |
| 99 | 99 | 101 | 100 | 99 | 102 |

# Why the Exponential Cutoff?

Ensemble of particles exchanging energies:



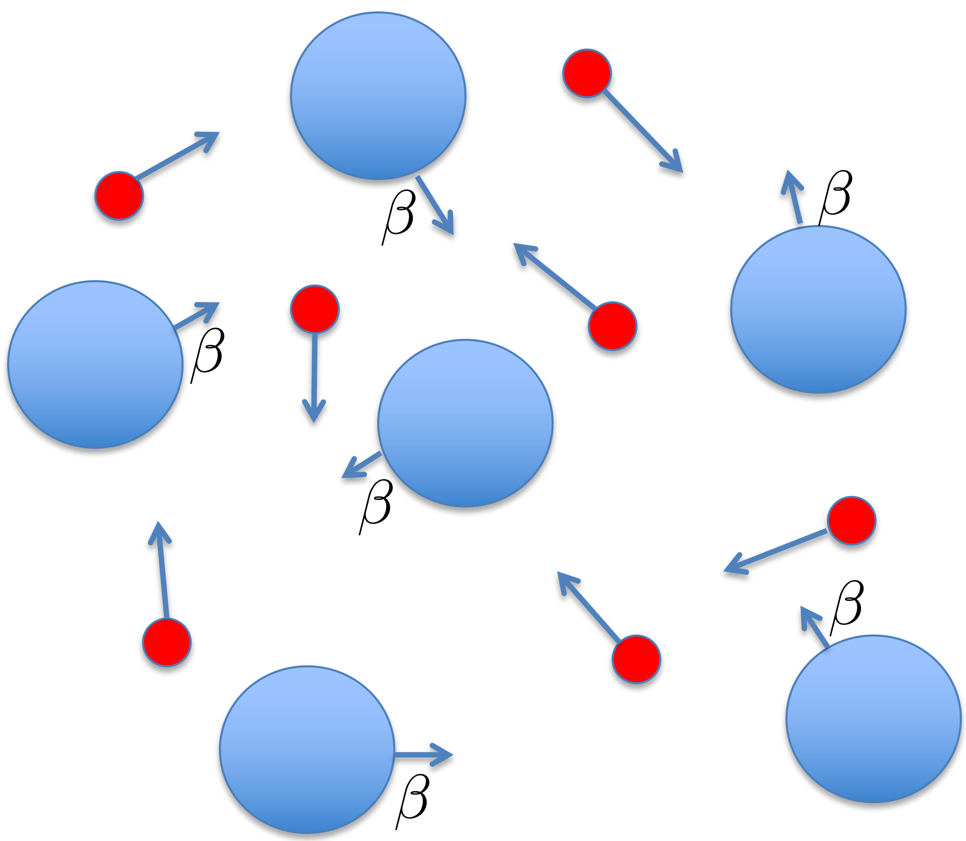
# But we don't always observe an exponential cutoff



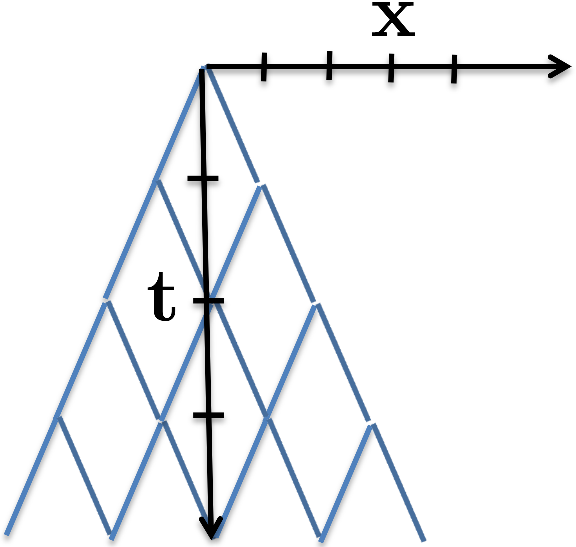
# The Origin of the Power-law Tail

$$\mathbf{D_{xx}D_{pp} \approx \beta_{scat}^2 p^2}$$

Note the assumption here that magnetic turbulence exists



# Random Walks




$$\gamma(\mathbf{t}+\mathbf{1}) = \mathbf{t}!$$

$$\gamma(\mathbf{t}+\mathbf{1}) = \int_{\mathbf{0}}^{\infty} \mathbf{x}^{\mathbf{t}} \mathbf{e}^{-\mathbf{x}} \mathbf{dx}$$

$$\mathbf{f}(\mathbf{x},\mathbf{t}) = \gamma(\mathbf{t}+\mathbf{1})/[\gamma([\mathbf{t}-\mathbf{x}]/\mathbf{2}+\mathbf{1})\gamma([\mathbf{x}+\mathbf{t}]/\mathbf{2}+\mathbf{1})]/(\mathbf{2}^{\mathbf{t}})$$

$$\mathbf{f}(\mathbf{x},\mathbf{t}) \approx \frac{\mathbf{e}^{-\mathbf{x}^{\mathbf{2}}/(\mathbf{2t})}}{[\pi/(\mathbf{t}/\mathbf{2})]^{\mathbf{1}/\mathbf{2}}}$$

# Random Walks

Spatial spread: $$\frac{dN}{dx} \propto e^{-x^2/4D_{xx}t}$$

$$\frac{dN}{dx} \propto e^{-x^2/4c^2 t_{scat} t}$$

$$D_{xx}D_{pp} \approx \beta_{scat}^2 p^2$$

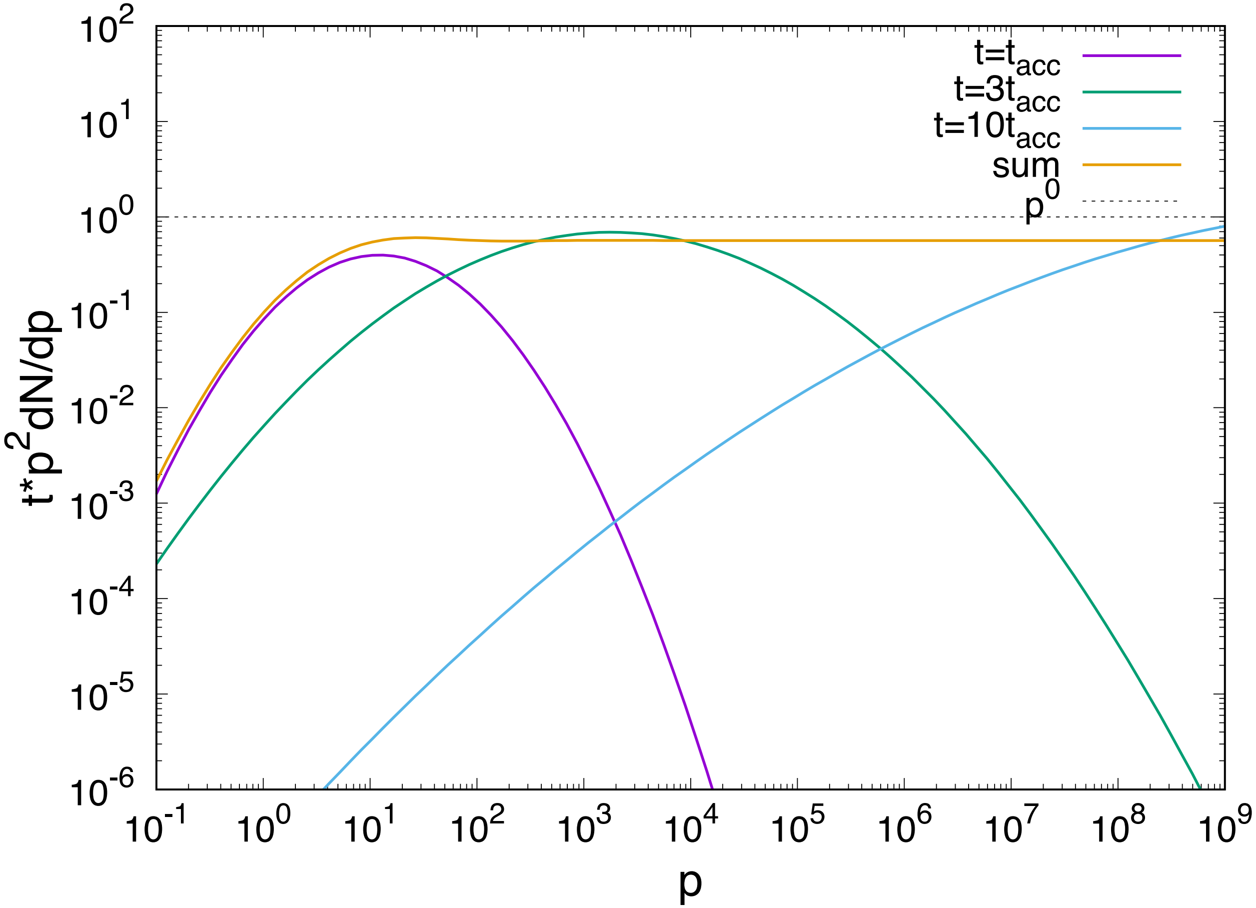
$$t_{acc} \approx \frac{t_{scat}}{\beta^2}$$

Momentum spread: $$\frac{\Delta p}{p} \propto \beta$$

$$\frac{dN}{dp} \propto e^{-(\ln p)^2/4(D_{pp}/p^2)t}$$

$$\frac{dN}{dp} \propto e^{-(\ln p)^2/4(t/t_{acc})}$$

# Green's Function for Stochastic Acceleration



# Why Does Magnetic Turbulence Exist?

WARNING- EXISTENCE QUESTIONS ARE HARD!

# Hydro Turbulence

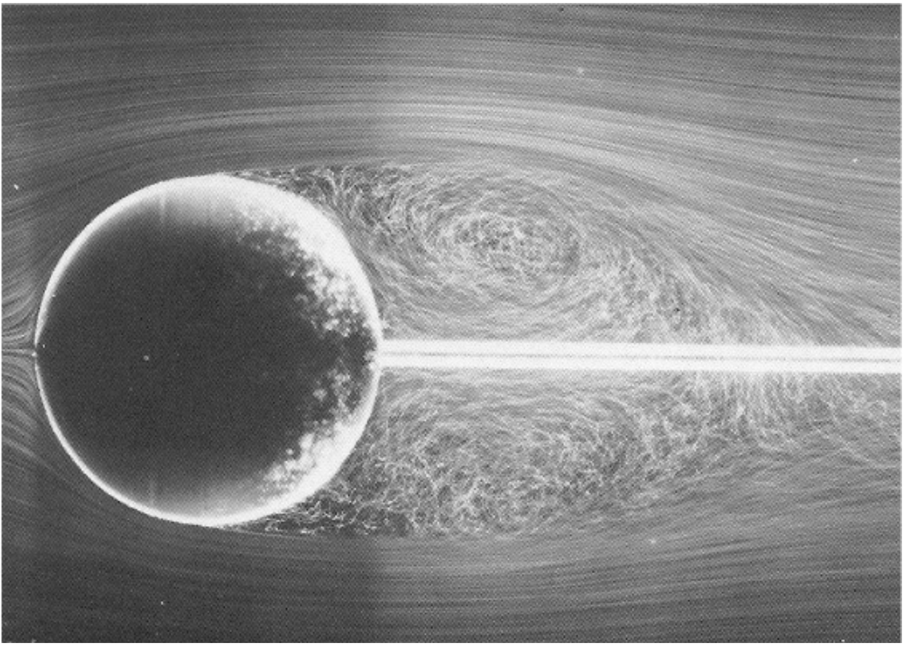
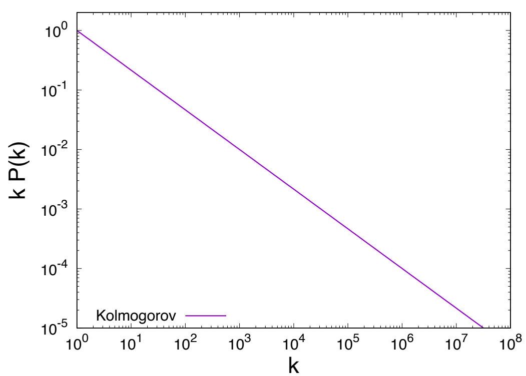
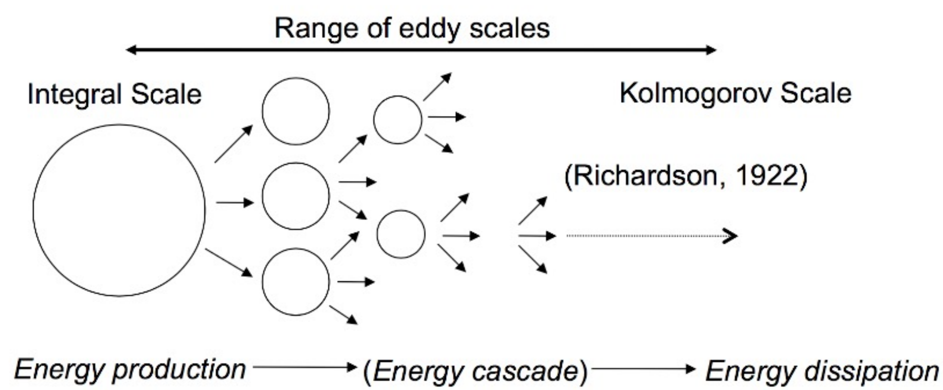


Image from University of Sydney

Richardson, 1922

> *Big whorls have little whorls*
> *That feed on their velocity;*
> *And little whorls have lesser whorls*
> *And so on to viscosity.*



# Hydrodynamics

A brief comment-

$$\frac{\partial \rho \mathbf{v}}{\partial \mathbf{t}} + \nabla \cdot \mathbf{P} = \rho \mathbf{g}$$

Momentum flux conservation

$$\mathbf{P} = \mathbf{pI} + \rho \mathbf{vv}$$

Spatial part of stress energy tensor

$$\rho \frac{\partial \mathbf{v}}{\partial \mathbf{t}} + \rho(\mathbf{v} \cdot \nabla)\mathbf{v} = -\nabla \mathbf{p} + \rho \mathbf{g}$$

# Magneto-Hydrodynamics

A brief comment-

$$\frac{\partial \rho \mathbf{v}}{\partial \mathbf{t}} + \nabla \cdot (\mathbf{P} - \mathbf{P_M}) = \rho \mathbf{g}$$

Momentum flux conservation

$$\mathbf{P} = \mathbf{pI} + \rho \mathbf{vv}$$

$$\mathbf{P_M} = -\frac{\mathbf{B^2}}{\mathbf{8}\pi}\mathbf{I} + \frac{\mathbf{BB}}{\mathbf{4}\pi}$$

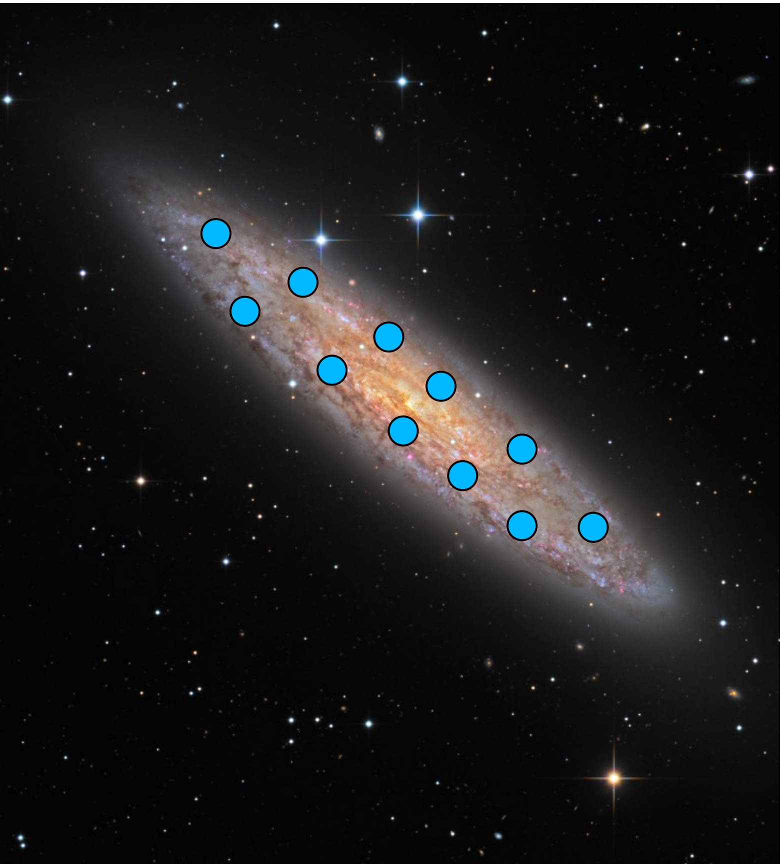
Maxwell stress tensor

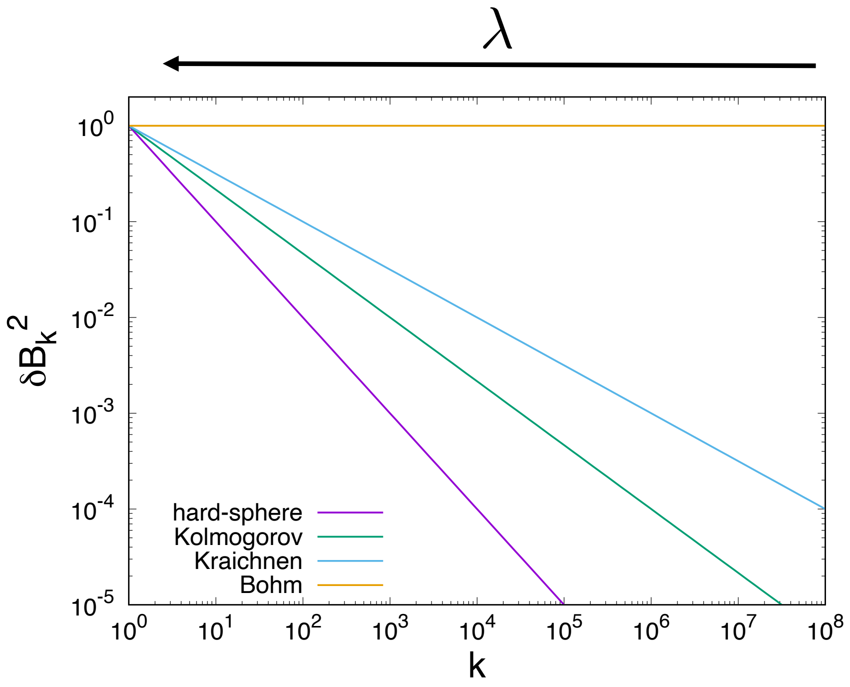
# Galactic Magneto-Hydro Turbulence

One of the key drivers is thought to be Supernova explosions

$$\delta \mathbf{B^2} = \int \frac{\mathbf{d}(\delta \mathbf{B^2})}{\mathbf{d} \ln \mathbf{k}} \mathbf{d} \ln \mathbf{k} = \int \delta \mathbf{B_k^2} \mathbf{d} \ln \mathbf{k}$$

$$\delta \mathbf{B_k^2} = \delta \mathbf{B_0^2} \left( \frac{\mathbf{k}}{\mathbf{k_0}} \right)^{\mathbf{1}-\alpha}$$

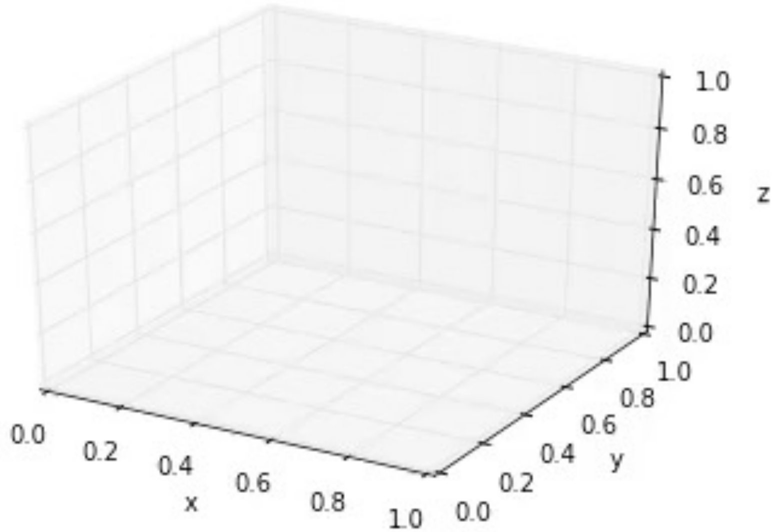


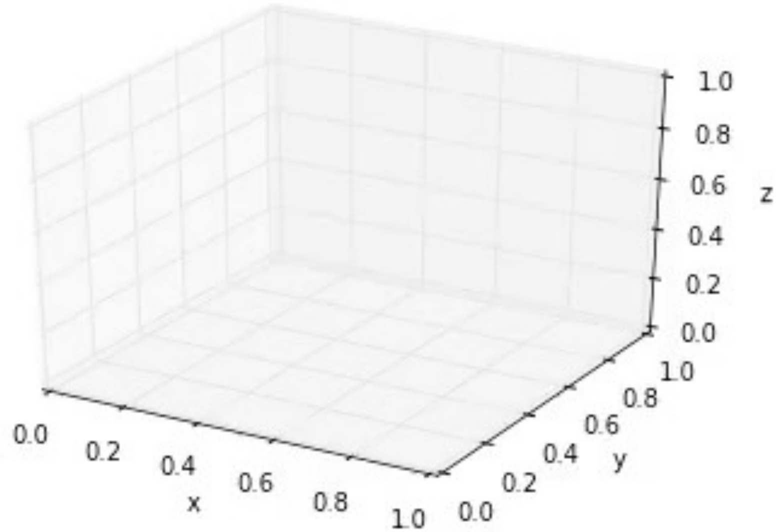



Note for MHD turbulence, the theoretically expected turbulence index is still debated

# Charged Particles in Magnetic Fields

Note- a lot of what you **may have** studied about charged particle propagation in magnetic fields **likely** assumed magnetic field variation was on much longer length scales than particle Larmor radius.

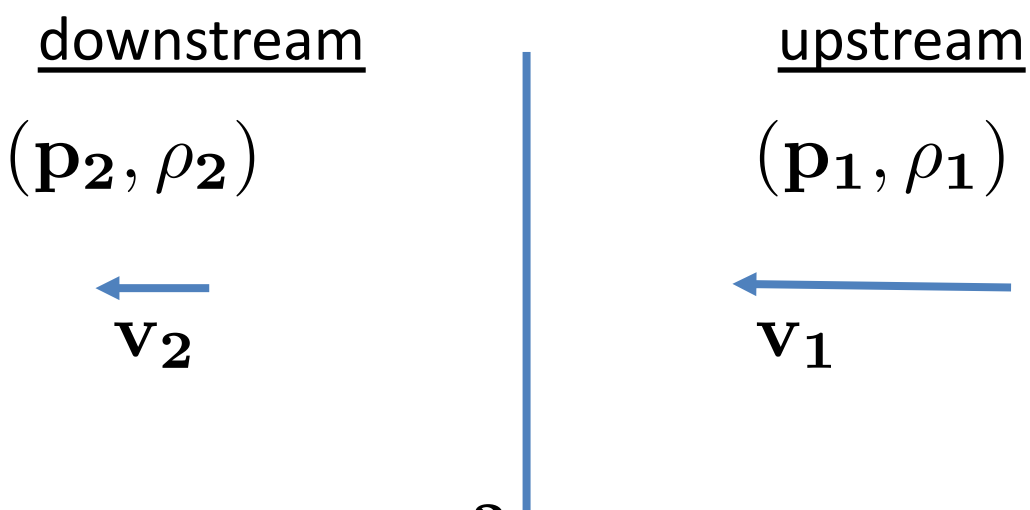


# What Do Shocks Do?

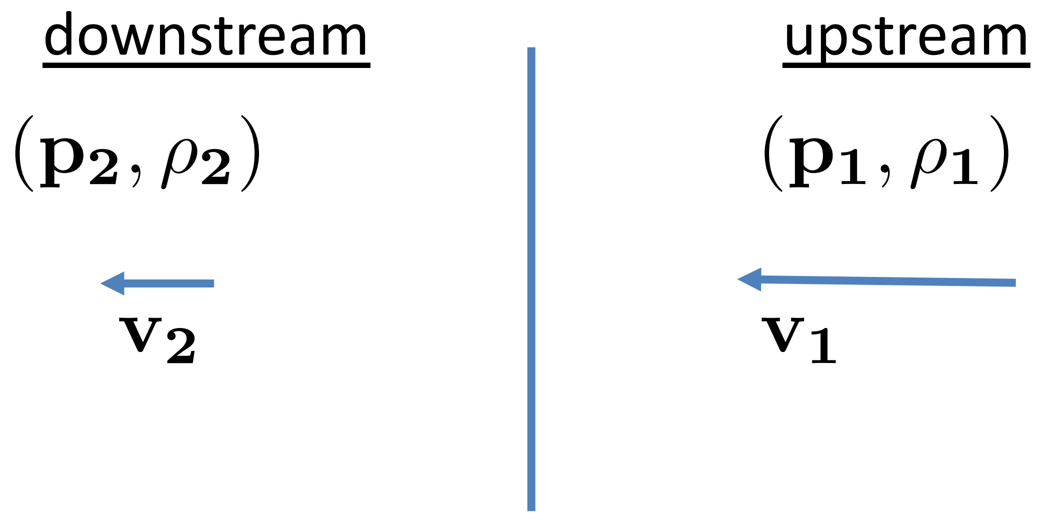
# Reminder: (Non-Rel.) Shocks

The fastest speed information in plasmas can be transmitted is the sound speed. When plasmas travel faster than this, they set up a shock- the upstream region is not able to know what is coming (**a surprise**!).




Shock converts ram pressure ( $\rho \mathbf{v}^2$ ) into thermal pressure ( $\mathbf{p}$ )

# Collisional Shock- Conservation Conditions




Number Flux: $$\rho_1 \mathbf{v_1} = \rho_2 \mathbf{v_2}$$

Momentum Flux: $$\mathbf{p_1} + \rho_1 \mathbf{v_1^2} = \mathbf{p_2} + \rho_2 \mathbf{v_2^2}$$

Energy Flux: $$\mathbf{w_1 v_1} + \frac{1}{2}\rho_1 \mathbf{v_1^3} = \mathbf{w_2 v_2} + \frac{1}{2}\rho_2 \mathbf{v_2^3}$$

# Collisional Shock- Enthalpy

$$\gamma = \frac{\mathbf{w}_{\mathbf{nonrel.}}}{\mathbf{e}}$$

$$= \frac{\mathbf{e}+\mathbf{p}}{\mathbf{e}}$$

$$\mathbf{e} = \frac{\mathbf{p}}{\gamma - \mathbf{1}}$$

$$\mathbf{w}_{\mathbf{nonrel.}} = \frac{\gamma}{\gamma - \mathbf{1}}\mathbf{p}$$

$$\mathbf{w}_{\mathbf{rel.}} = \frac{\gamma}{\gamma - \mathbf{1}}\mathbf{p} + \rho$$

$$= \mathbf{w}_{\mathbf{nonrel.}} + \rho$$

# Collisional Shock- Cold Shock Case

Momentum Flux:

$$\rho_1 v_1^2 = p_2 + \rho_2 v_2^2$$

$$\frac{p_2}{\rho_1 v_1^2} = \left(1 - \frac{v_2}{v_1}\right)$$

Energy Flux:

$$\frac{1}{2}\rho_1 v_1^3 = \left(\frac{\gamma}{\gamma - 1}\right) p_2 v_2 + \frac{1}{2}\rho_2 v_2^3$$

$$\frac{2\gamma}{\gamma - 1}\frac{p_2 v_2}{\rho_1 v_1^3} = \left(1 - \left(\frac{v_2}{v_1}\right)^2\right) = \left(1 - \frac{v_2}{v_1}\right)\left(1 + \frac{v_2}{v_1}\right)$$

# Collisional Shock- Cold Shock Case

$$\frac{\mathbf{v_2}}{\mathbf{v_1}}\left(\mathbf{1}-\frac{\mathbf{v_2}}{\mathbf{v_1}}\right)=\left(\frac{\gamma-\mathbf{1}}{\mathbf{2}\gamma}\right)\left(\mathbf{1}-\left(\frac{\mathbf{v_2}}{\mathbf{v_1}}\right)^{\mathbf{2}}\right)$$

$$\left(\frac{\mathbf{v_2}}{\mathbf{v_1}}-\mathbf{1}\right)\left(\frac{\mathbf{v_2}}{\mathbf{v_1}}-\left(\frac{\gamma-\mathbf{1}}{\gamma+\mathbf{1}}\right)\right)=\mathbf{0}$$

So what are collisional shocks good for?

# Collisional Shock- Cold Shock Case

$$\frac{\mathbf{v_2}}{\mathbf{v_1}}\left(1-\frac{\mathbf{v_2}}{\mathbf{v_1}}\right)=\left(\frac{\gamma-1}{2\gamma}\right)\left(1-\left(\frac{\mathbf{v_2}}{\mathbf{v_1}}\right)^2\right)$$

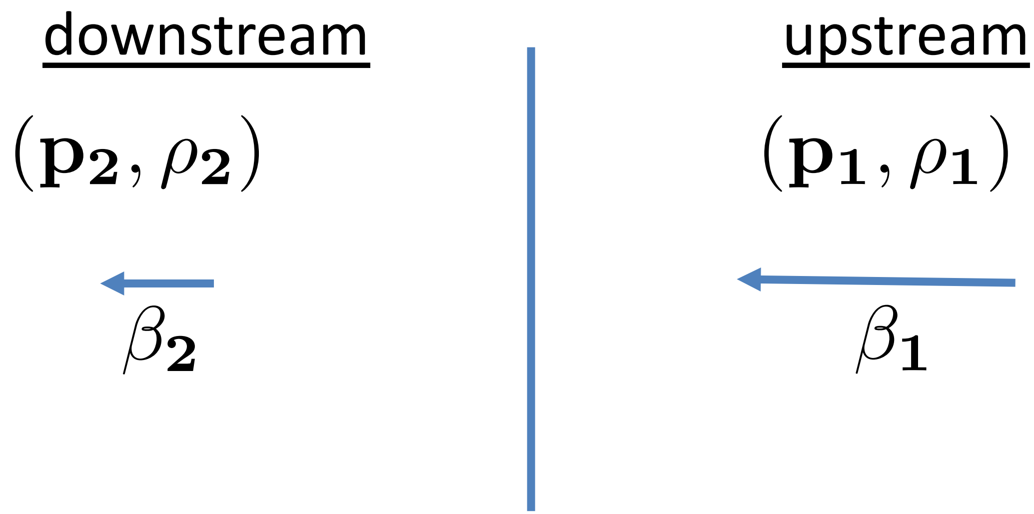
$$\left(\frac{\mathbf{v_2}}{\mathbf{v_1}}-1\right)\left(\frac{\mathbf{v_2}}{\mathbf{v_1}}-\left(\frac{\gamma-1}{\gamma+1}\right)\right)=0$$

Eg: $\gamma=\frac{5}{3}$ → $\frac{\beta_2}{\beta_1}=\frac{1}{4}$

So what are collisional shocks good for?
Stimulating the unstimulated degrees of freedom in the system where momentum/energy can be stored

# Relativistic Shocks

How does the compression ratio result change for relativistic shocks




Number Flux: $$\rho_\mathbf{1}\beta_\mathbf{1}\mathbf{\Gamma_1} = \rho_\mathbf{2}\beta_\mathbf{2}\mathbf{\Gamma_2}$$

Momentum Flux: $$\mathbf{p_1} + \mathbf{w_1}\beta_\mathbf{1}^\mathbf{2}\mathbf{\Gamma_1^2} = \mathbf{p_2} + \mathbf{w_2}\beta_\mathbf{2}^\mathbf{2}\mathbf{\Gamma_2^2}$$

Energy Flux: $$\mathbf{w_1}\beta_\mathbf{1}\mathbf{\Gamma_1^2} = \mathbf{w_2}\beta_\mathbf{2}\mathbf{\Gamma_2^2}$$

# Upsream and Downstream Enthalpy

$$\mathbf{w_{rel.}} = \frac{\gamma}{\gamma - \mathbf{1}}\mathbf{p} + \rho$$

$$\mathbf{w_1} = \rho_\mathbf{1}$$

$$\mathbf{w_2} = \frac{\gamma}{\gamma - \mathbf{1}}\mathbf{p_2} + \rho_\mathbf{2}$$

# Relativistic Shocks

Momentum Flux:

$$\mathbf{p_1} + \left(\frac{\gamma}{\gamma - \mathbf{1}}\mathbf{p_1} + \rho_\mathbf{1}\right)\beta_\mathbf{1}^\mathbf{2}\mathbf{\Gamma}_\mathbf{1}^\mathbf{2} = \mathbf{p_2} + \left(\frac{\gamma}{\gamma - \mathbf{1}}\mathbf{p_2} + \rho_\mathbf{2}\right)\beta_\mathbf{2}^\mathbf{2}\mathbf{\Gamma}_\mathbf{2}^\mathbf{2}$$

Energy Flux:

$$\left(\frac{\gamma}{\gamma - \mathbf{1}}\mathbf{p_1} + \rho_\mathbf{1}\right)\beta_\mathbf{1}\mathbf{\Gamma}_\mathbf{1}^\mathbf{2} = \left(\frac{\gamma}{\gamma - \mathbf{1}}\mathbf{p_2} + \rho_\mathbf{2}\right)\beta_\mathbf{2}\mathbf{\Gamma}_\mathbf{2}^\mathbf{2}$$

# Cold Relativistic Shocks

Momentum Flux:

$$\rho_1 \beta_1^2 \Gamma_1^2 = p_2 + \left(\frac{\gamma}{\gamma-1} p_2 + \rho_2\right) \beta_2^2 \Gamma_2^2$$

$$\rho_1 \beta_1^2 \Gamma_1^2 - \rho_2 \beta_2^2 \Gamma_2^2 = p_2 \left[1 + \left(\frac{\gamma}{\gamma-1}\right) \beta_2^2 \Gamma_2^2\right]$$

Energy Flux:

$$\rho_1 \beta_1 \Gamma_1^2 = \left(\frac{\gamma}{\gamma-1} p_2 + \rho_2\right) \beta_2 \Gamma_2^2$$

$$\rho_1 \beta_1 \Gamma_1 (\Gamma_1 - 1) = \frac{\gamma}{\gamma-1} p_2 \beta_2 \Gamma_2^2 + \rho_2 \beta_2 \Gamma_2 (\Gamma_2 - 1)$$

# Relativistic Shocks

Momentum Flux:

$$\frac{\mathbf{p_2}}{\mathbf{\Gamma_1^2}\beta_\mathbf{1}^\mathbf{2}\rho_\mathbf{1}}\left[\mathbf{1}+\mathbf{\Gamma_2^2}\beta_\mathbf{2}^\mathbf{2}\left(\frac{\gamma}{\gamma-\mathbf{1}}\right)\right]=\left(\mathbf{1}-\frac{\mathbf{\Gamma_2}\beta_\mathbf{2}}{\mathbf{\Gamma_1}\beta_\mathbf{1}}\right)$$

Energy Flux:

$$\left(\frac{\gamma}{\gamma-\mathbf{1}}\right)\frac{\mathbf{\Gamma_2^2 p_2}\beta_\mathbf{2}}{\mathbf{\Gamma_1^2}\rho_\mathbf{1}\beta_\mathbf{1}}=\left(\mathbf{1}-\frac{(\mathbf{\Gamma_2}-\mathbf{1})}{(\mathbf{\Gamma_1}-\mathbf{1})}\right)$$

# Relativistic Shocks

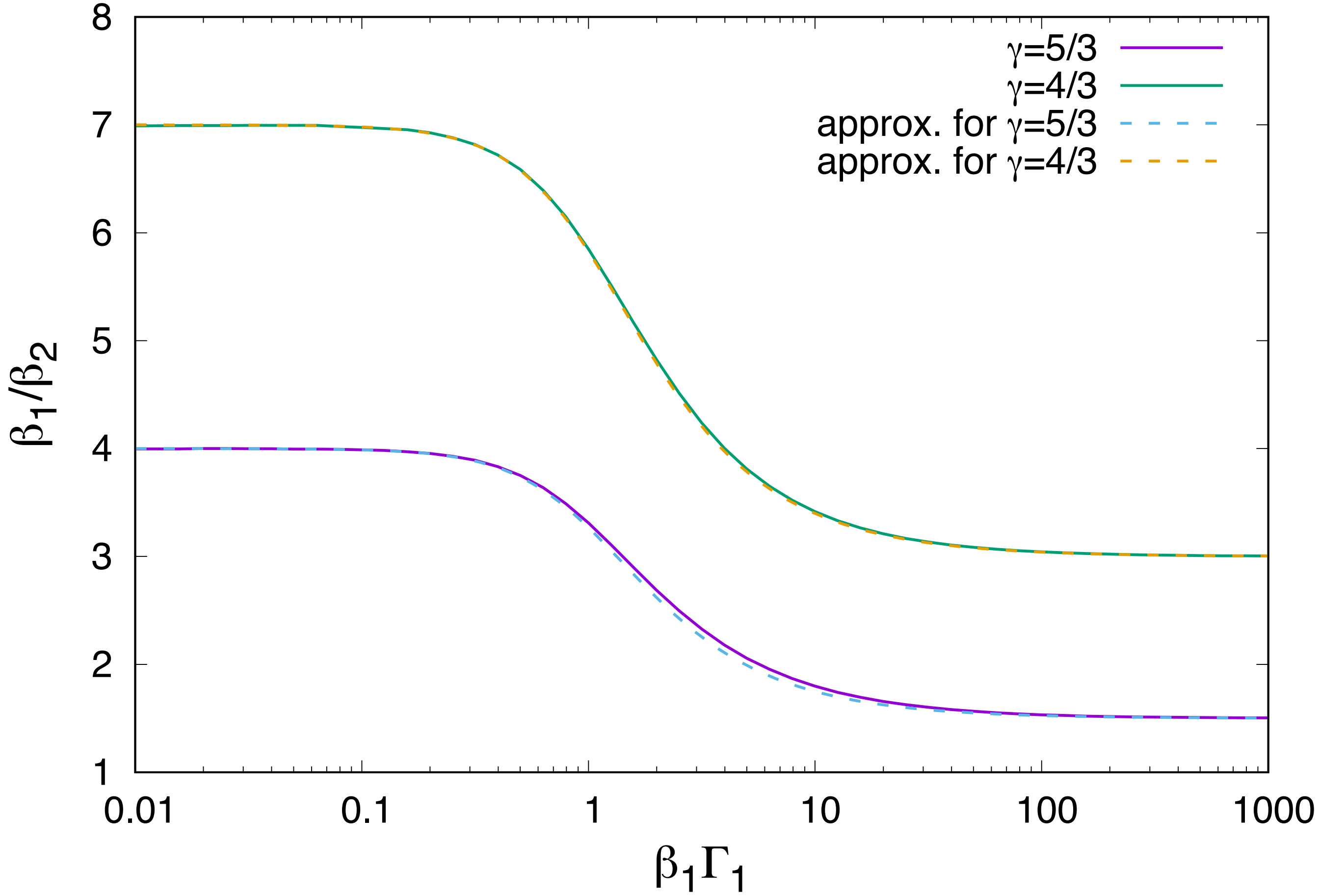
$$\frac{1-\frac{\Gamma_2\beta_2}{\Gamma_1\beta_1}}{1+\Gamma_2^2\beta_2^2\frac{\gamma}{\gamma-1}}=\frac{1-\frac{\Gamma_2-1}{\Gamma_1-1}}{\Gamma_2^2\beta_2\frac{\gamma}{\gamma-1}}$$

$$1+\Gamma_2^2\beta_2^2\left(\frac{\gamma}{\gamma-1}\right)=\Gamma_2^2\beta_2\left(\frac{\gamma}{\gamma-1}\right)$$

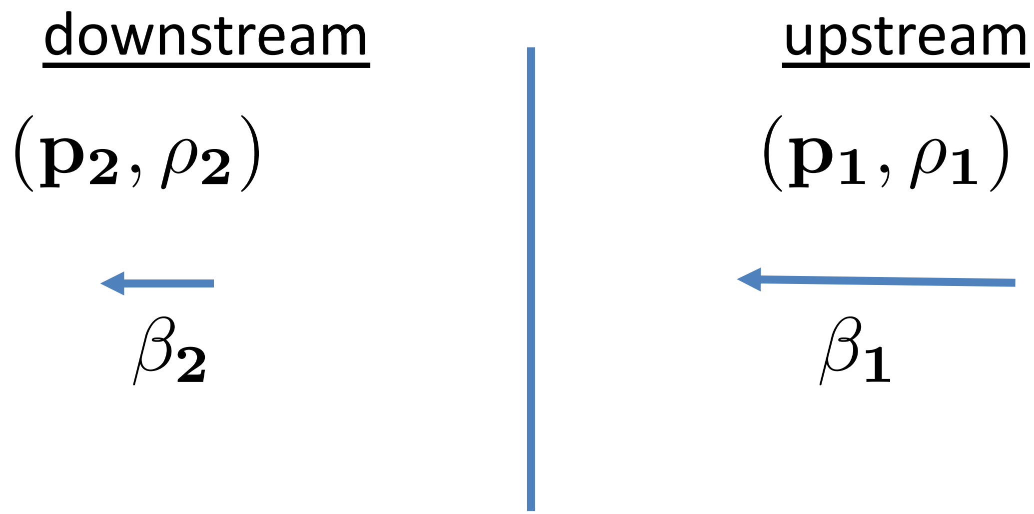
$$(\beta_2-1)(\beta_2-(\gamma-1))=0$$

Eg: $\gamma=\frac{4}{3}$ → $\frac{\beta_2}{\beta_1}=\frac{1}{3}$

# Shock Compression Ratio vs Upstream Velocity



# Dowstream Partition of the Upstream Ram Pressure




[viewed in shock restframe]

$$\mathbf{p_2} = \frac{3}{4}\rho_1\beta_1^2$$

$$\rho_2\beta_2^2 = \frac{1}{4}\rho_1\beta_1^2$$

$$\rho_1\beta_1^2$$

# Rel. Shock- Dowstream Partition of the Upstream Ram Pressure

downstream

$$(\mathbf{p_2}, \rho_2)$$

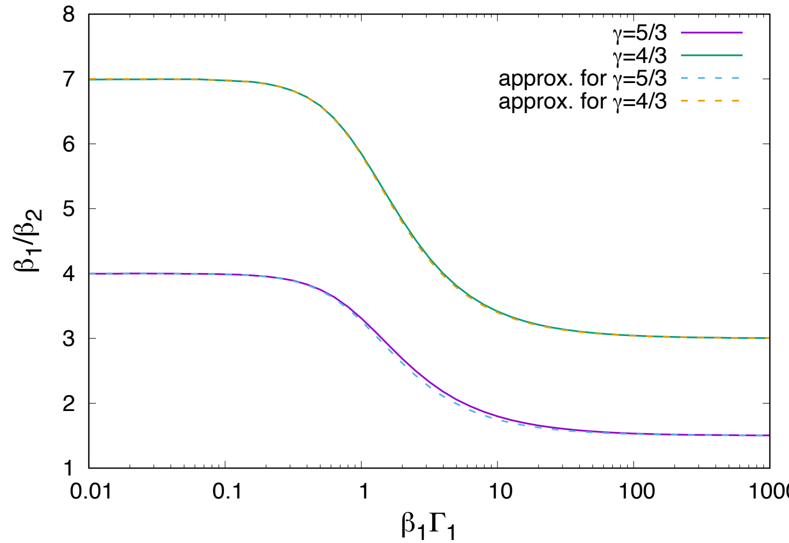
$$\beta_2 \mathbf{\Gamma_2}$$

upstream

$$(\mathbf{p_1}, \rho_1)$$

$$\beta_1 \mathbf{\Gamma_1}$$

[viewed in shock restframe]




$$\mathbf{p_2} = \frac{\mathbf{2}}{\mathbf{3}} \rho_1 \beta_1^2 \mathbf{\Gamma_1^2}$$

$$\mathbf{w_2} \beta_2^2 \mathbf{\Gamma_2^2} = \frac{\mathbf{1}}{\mathbf{3}} \rho_1 \beta_1^2 \mathbf{\Gamma_1^2}$$

$$\rho_1 \beta_1^2 \mathbf{\Gamma_1^2}$$

# Rel. Shock- Dowstream Partition of the Upstream Ram Pressure

$$\mathbf{p_2^{th}}$$

$$\mathbf{p_2^{ram}}$$

$$\mathbf{p_{CR}}$$

$$\mathbf{p_B}$$

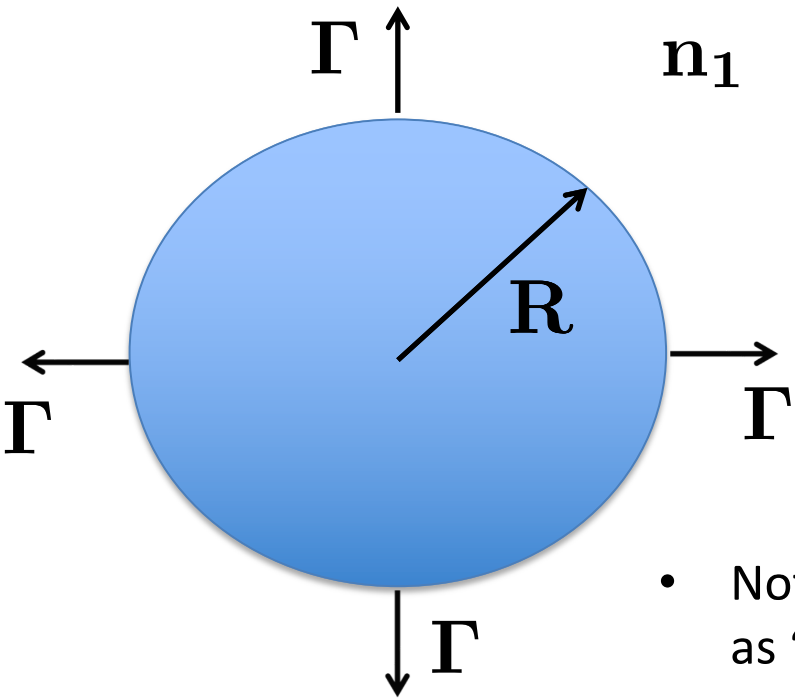
$$\rho_1\beta_1^2\Gamma_1^2$$

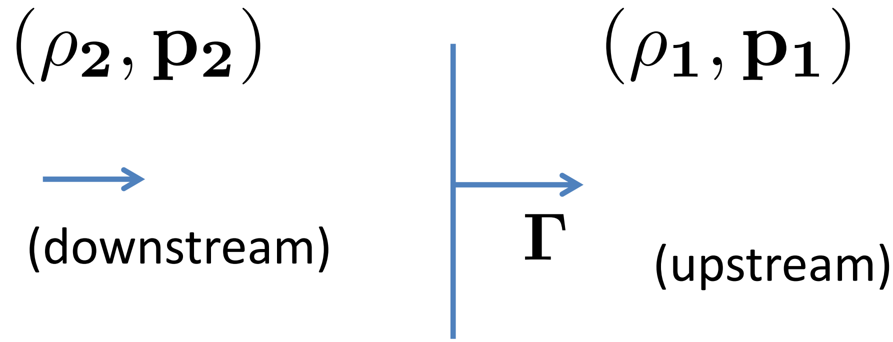
$$\varepsilon = \frac{\mathbf{p}}{\rho_1\beta_1^2\Gamma_1^2}$$

# Why are GRBs Interesting?

IMPORTANT QUESTION! WILL RETURN TO THIS QUESTION IN A WHILE

# What Are GRBs?




[viewed in upstream restframe]

- Not actually isotropic outflows, but can be considered as "quasi-isotropic" since $\theta_{jet}>1/\Gamma$
- $E_{iso}\sim10^{54}$ erg is close to Gravitational binding energy limit
- Extremely efficient emitters in terms of converting kinetic energy flux to radiation

# Relativistic Shocks

Downstream magnetic field partition of upstream ram pressure:

$$\varepsilon_{\mathbf{B}} = \frac{\mathbf{U_B}}{\rho_{\mathbf{1}}\beta_{\mathbf{1}}^{\mathbf{2}}\mathbf{\Gamma}_{\mathbf{1}}^{\mathbf{2}}}$$

For

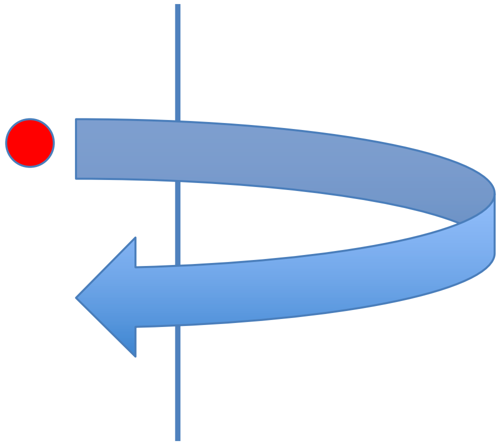
$$\varepsilon_{\mathbf{B}} = \mathbf{0.1} \qquad \mathbf{n_1} = \mathbf{1\ cm^{-3}} \qquad \beta_{\mathbf{1}}\mathbf{\Gamma_1} = \mathbf{10}$$

$$\mathbf{B} \approx \mathbf{0.6\ G}$$

$$\varepsilon_{\mathbf{B}} = \mathbf{10^{-5}} \qquad \mathbf{n_1} = \mathbf{1\ cm^{-3}} \qquad \beta_{\mathbf{1}}\mathbf{\Gamma_1} = \mathbf{10}$$

$$\mathbf{B} \approx \mathbf{6\ mG}$$

# Particle Acceleration and Magnetic Turbulence



- Isotropisation is caused by magnetic turbulence, its rate is described by the scattering time, which in Larmor time units is **η**

$$\mathbf{t_{scat}} = \eta \frac{\mathbf{R_{lar}}}{\mathbf{c}}$$

- Scattering agent velocity **β** dictates energy gain each crossing cycle

$$\mathbf{t_{acc.}} = \mathbf{\Delta t_{cyc}} \left(\mathbf{E}/\mathbf{\Delta E_{cyc}}\right) = \mathbf{t_{scat}}/\beta^{\mathbf{2}}$$

# Particle Accelerator Limits

$$\mathbf{t_{acc}} = \eta \frac{\mathbf{R_{lar}}}{\mathbf{c}\beta^{\mathbf{2}}}$$

$$\mathbf{t_{esc.}} = \frac{\mathbf{R}}{\mathbf{c}\beta}$$

[AM Hillas (1984)]

$$\mathbf{E_{max}} = \beta \mathbf{eBR}$$

$$\mathbf{L_B} = \mathbf{U_B} 4\pi \mathbf{R^2} \beta \mathbf{c}$$

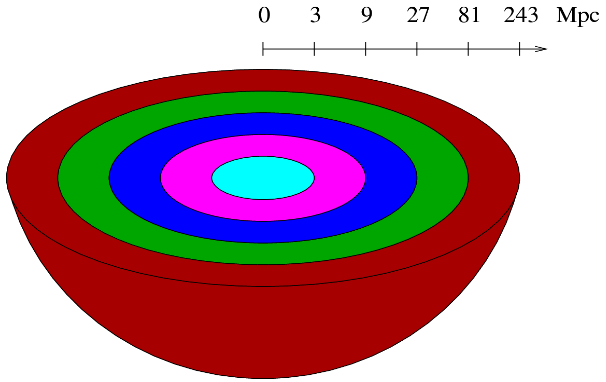
Under the assumption of equipartition of energy between kinetic energy and magnetic field:

[Lovelace et al. (1976)]

$$\mathbf{E_{max}} \lesssim \frac{\mathbf{Z}}{\eta} (\beta \mathbf{L_{KE}} \alpha \hbar)^{1/2} \approx \mathbf{10}\ \frac{\mathbf{Z}}{\eta} \left( \frac{\beta \mathbf{L_{KE}}}{\mathbf{3} \times \mathbf{10^{43}\ erg\ s^{-1}}} \right)^{1/2} \mathbf{EeV}$$

# Cosmic Ray Sources Have to be Local

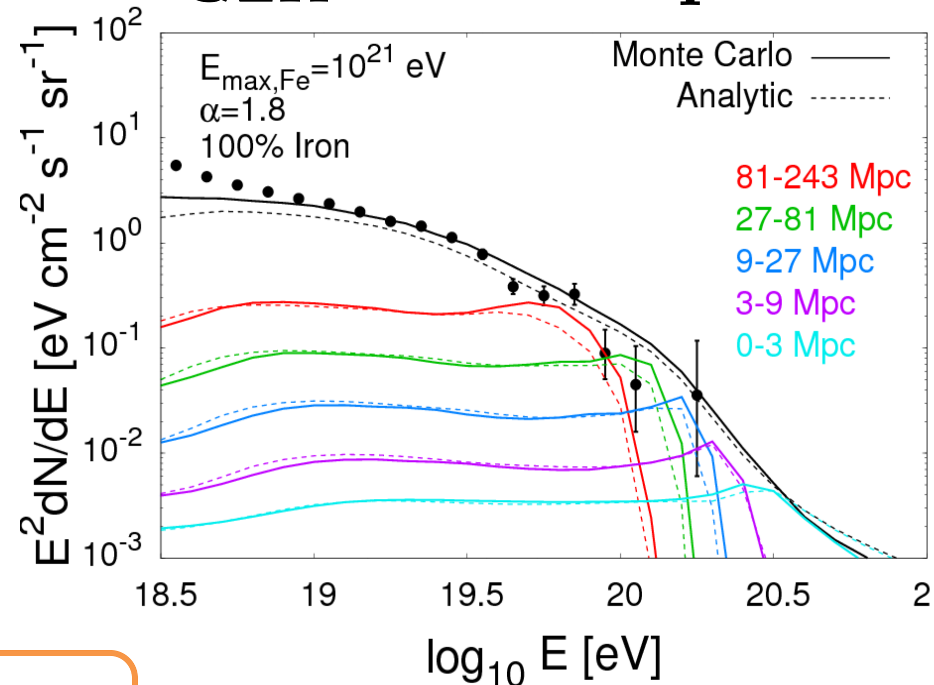
(logarithmic scale)




[A. Taylor et al., Phys Rev D (2011)]

[R. Lang and A. Taylor in prep.]

$$d_{GZK} \sim 100 \text{ Mpc}$$




$$\mathcal{L}_0 \approx 4 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$$

[E. Waxman, Astrophys. J. 452 (1995)]

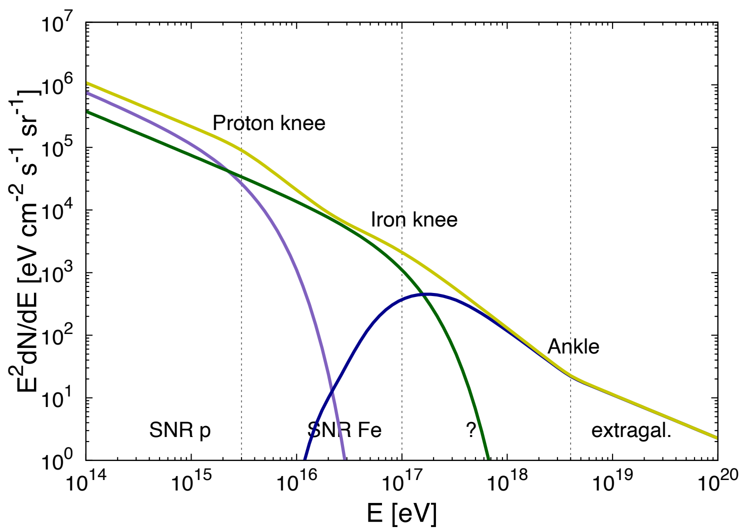
$$\mathcal{L}_0 \approx L_0 n_0$$
$$\approx E_0 \dot{n}_0$$

⇒

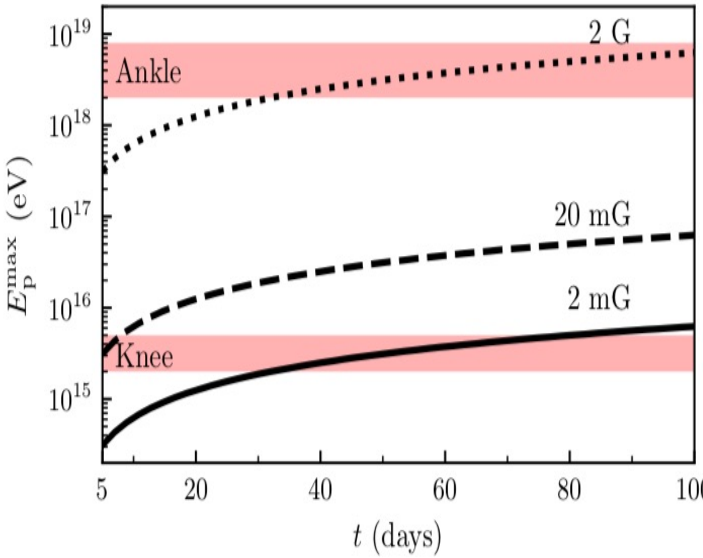
$$n_0 \sim 10^{-5} \text{ Mpc}^{-3}$$
$$\dot{n}_0 \sim 10^{-6} \text{ Mpc}^{-3} \text{ yr}^{-1}$$

Only AGN and GRB appears to satisfy these requirements as the sources of extragalactic cosmic rays

# GRB Outflows as a Cosmic Ray Source




- As the source expands, **CRs** can be accelerated to energies between the **knee and the ankle**
- If the *B*-field is as large as ~G -> possibility of **UHECRs**




[X. Rodrigues, A. Taylor, et al., ApJ 2019]

# Electron Acceleration with Cooling

$$t_{acc} = \eta \frac{R_{lar}}{c\beta^2}$$

$$t_{cool} = \frac{9}{8\pi\alpha}\left(\frac{U_{Bcrit}}{U_B}\right)\left(\frac{h}{E_e}\right)$$

$$B_{crit} = 4 \times 10^{13} G$$

$$E_e^{max} = \left(\frac{\eta^{-1/2}}{\alpha^{1/2}(B/B_{crit})^{1/2}}\right) m_e c^2$$

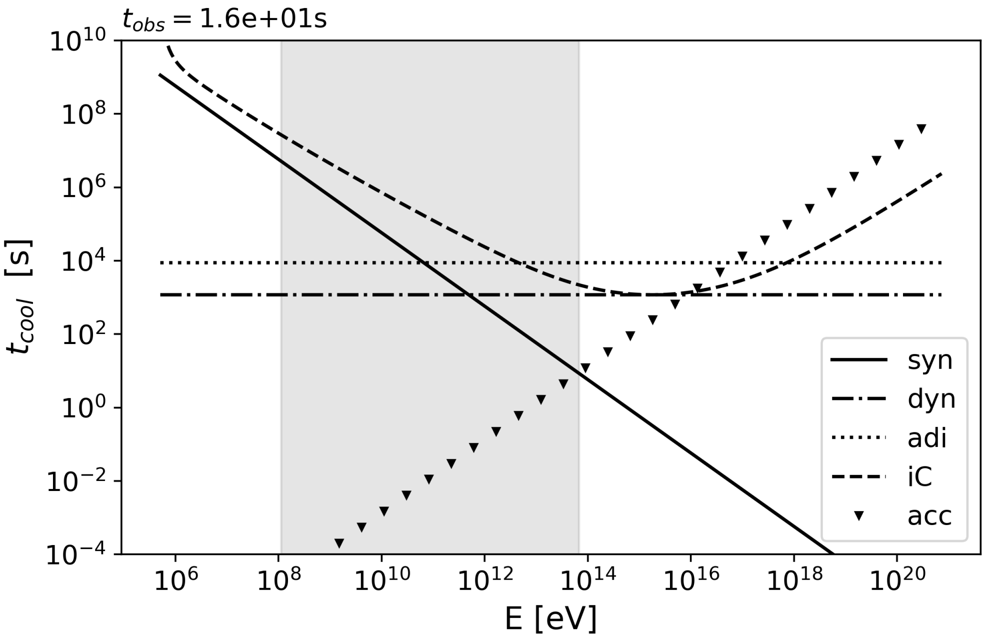
Maximum synchrotron energy tells us how efficient accelerator is!

$$E_\gamma^{sync} \approx \frac{9}{4}\eta^{-1}\beta^2 \frac{m_e}{\alpha}$$

Where do synchrotron cutoffs for AGN and GRB sit in energy?

# Energy Transport Equation

$$\frac{\partial \mathbf{n}}{\partial \mathbf{t}} = \frac{\partial}{\partial \mathbf{E}}\left(\frac{\mathbf{En}}{\tau_{\mathbf{cool}}}\right) + \mathbf{Q}(\mathbf{E})$$

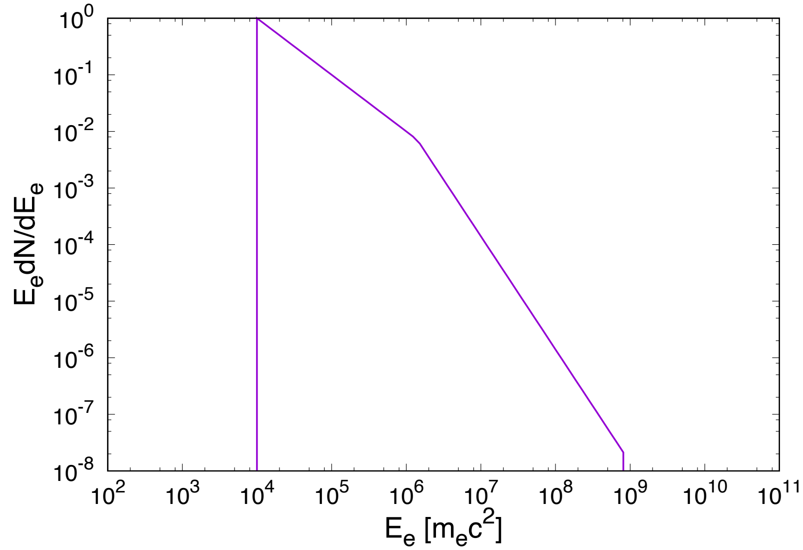



$$\tau_{\mathbf{cool}} = (\tau_{\mathbf{adi}}^{-\mathbf{1}} + \tau_{\mathbf{syn}}^{-\mathbf{1}})^{-\mathbf{1}}$$

# Steady State Electron Spectra

$$\mathbf{n_{ss} = \frac{\tau_{cool}}{E} \int_E^{\infty} Q(E) dE}$$

$$\mathbf{n_{ss} \approx Q\tau_{cool}}$$



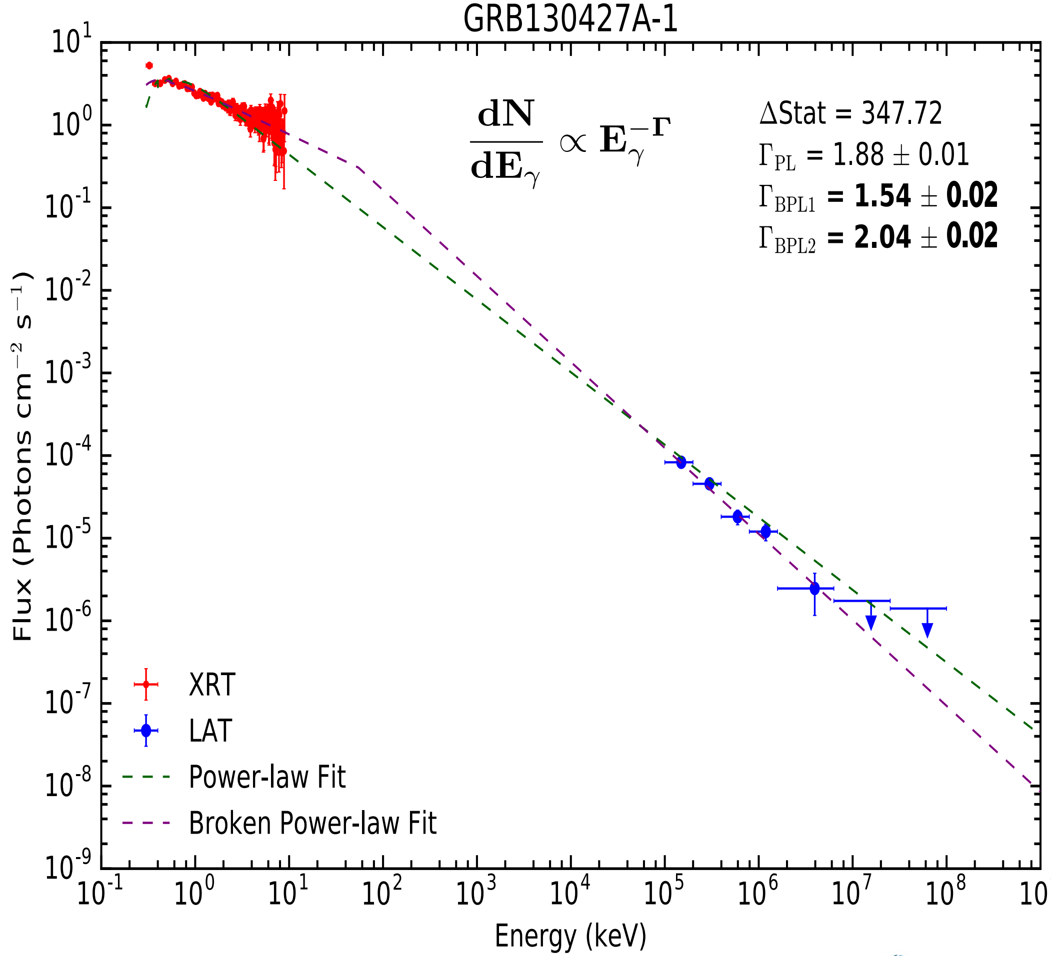
# No Synchrotron Cutoff of the Brightest GRB Seen by Fermi-LAT

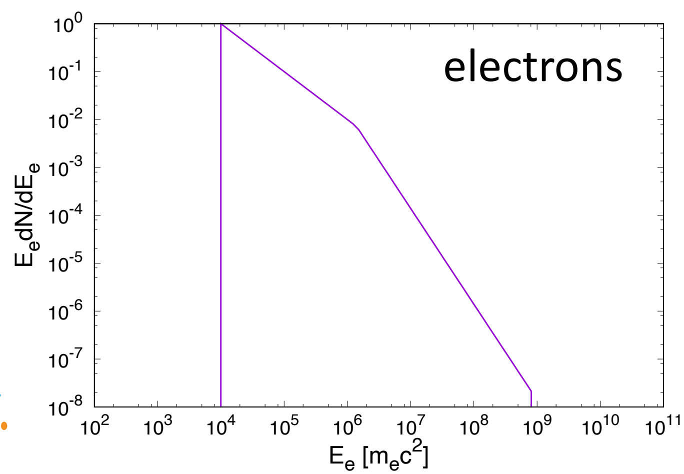
- GRBs at HE and VHE:
  ~12 GRBs per year Fermi-LAT

- However, most science learnt from brightest event- GRB130427A: 94 GeV max energy photon.

**VHE emission has been a decades-long mystery**

[Ajello et al., ApJ 863 138 (2018)]

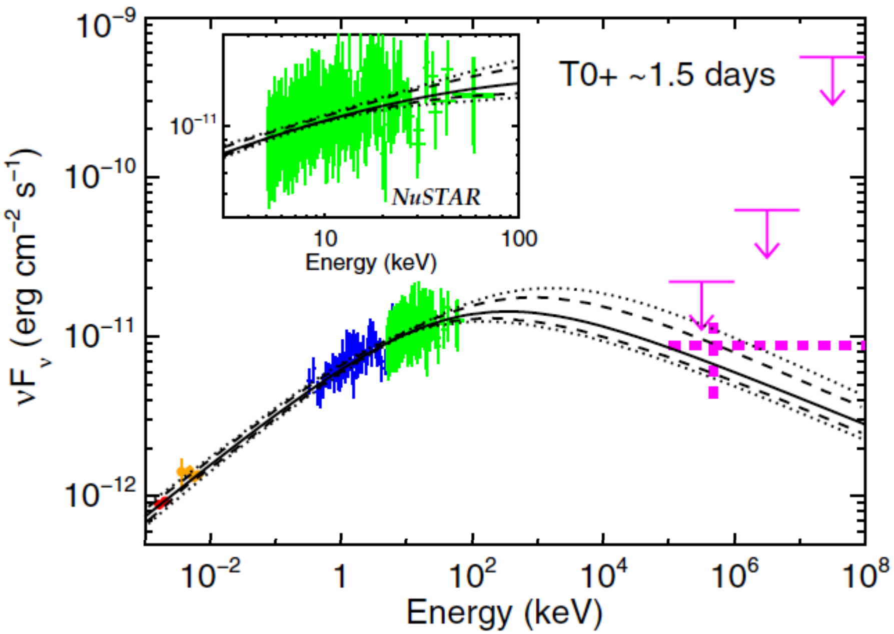


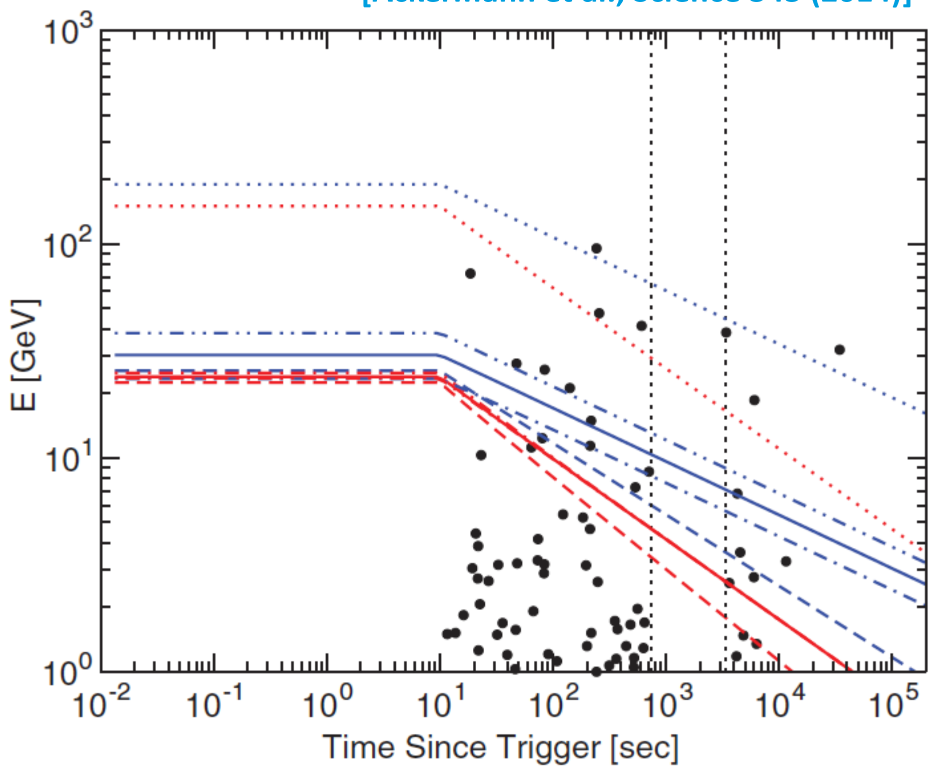

$t^{GBM}_{90}$ ~ 140 s, $t^{BAT}_{90}$ ~ 160 s
z = 0.34

# No Synchrotron Cutoff of the Brightest GRB Seen by Fermi-LAT

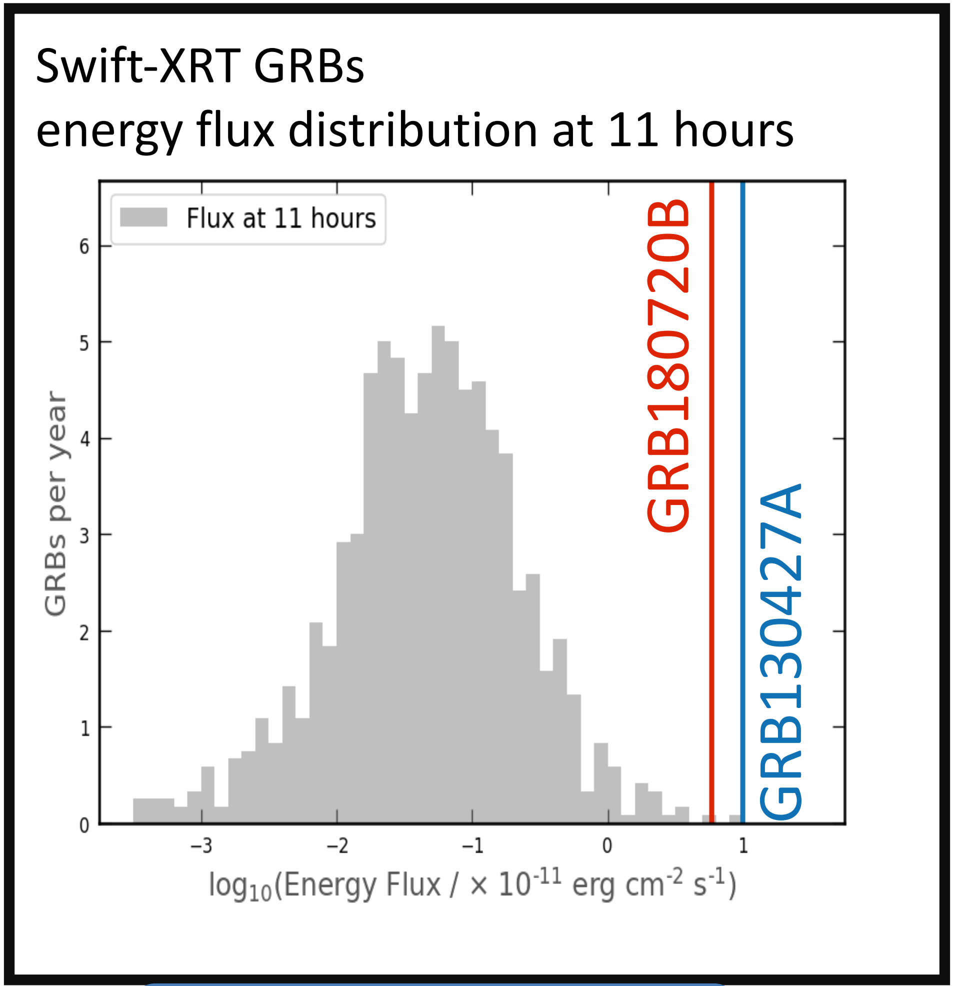
[Kouveliotou et al., ApJL 779 (2013)]




[Ackermann et al., Science 343 (2014)]

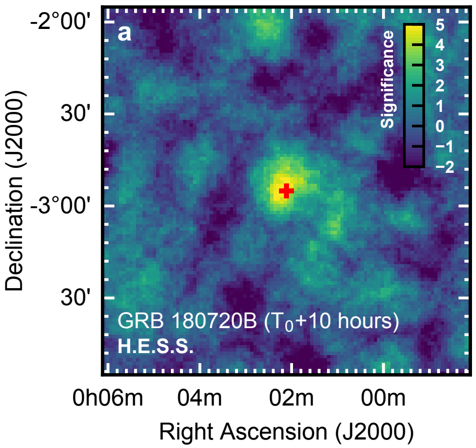


# GRB 180720B X-ray 11 hr Energy Flux in Comparison to Other Bright Bursts




- Fermi-LAT detection from $T_0$ to $T_0$+700 s (max. energy photon 5 GeV).
- Extremely bright burst:
  - 2nd brightest afterglow measured by Swift-XRT.
- Very similar x-ray light curve to GRB130427A and GRB190114C.

$$100\ \mathbf{GeV} < \mathbf{E}_\gamma < 440\ \mathbf{GeV}$$




$t^{GBM}_{90}$ ~ 50 s, $t^{BAT}_{90}$~ 100 s
z = 0.653

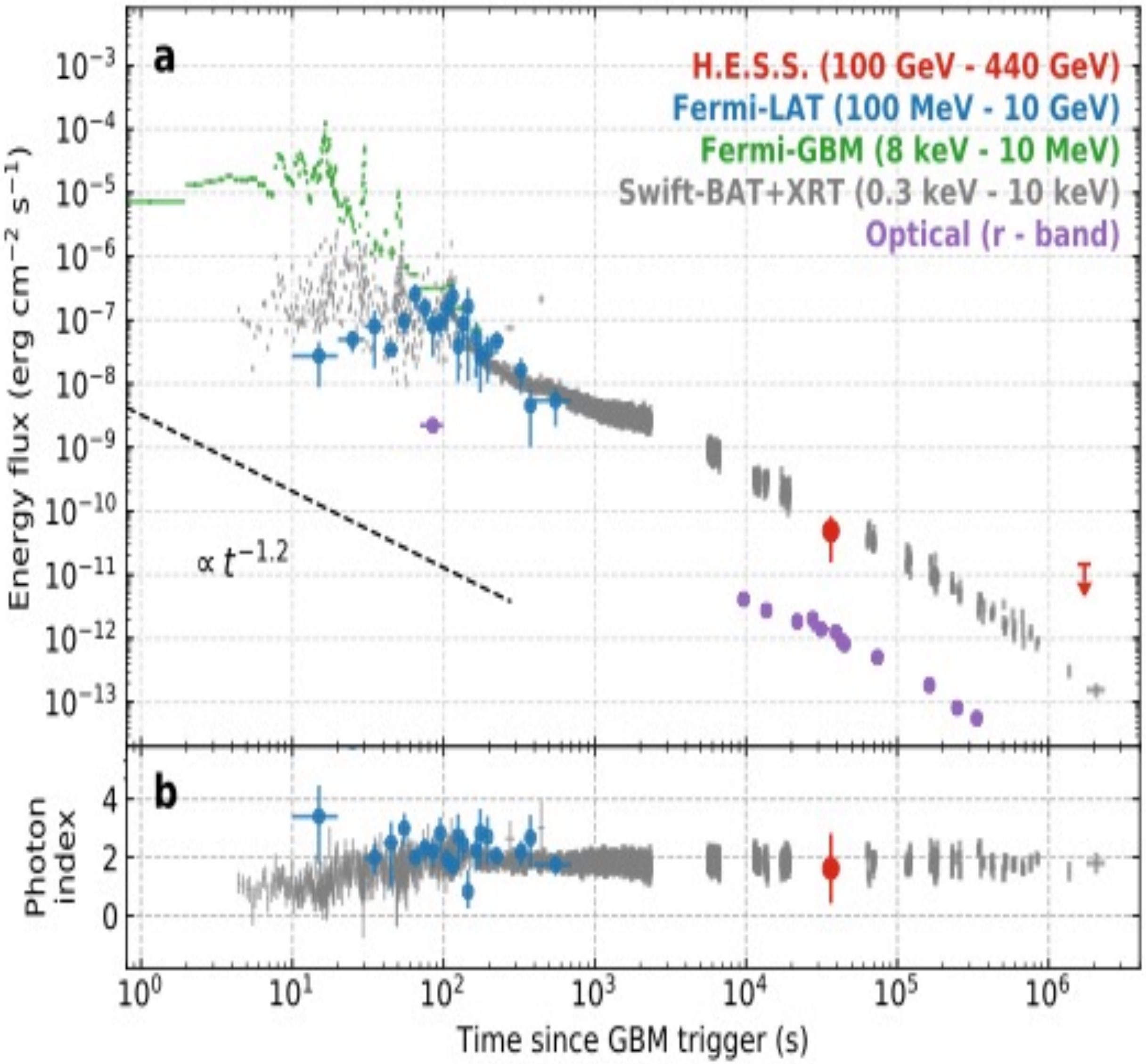
DESY.

[HESS- C. Hoishen, A. Taylor, et al., Nature 2019]

Andrew Taylor

H.E.S.S.

# GRB 180720B Multi-Wavelength Light Curve



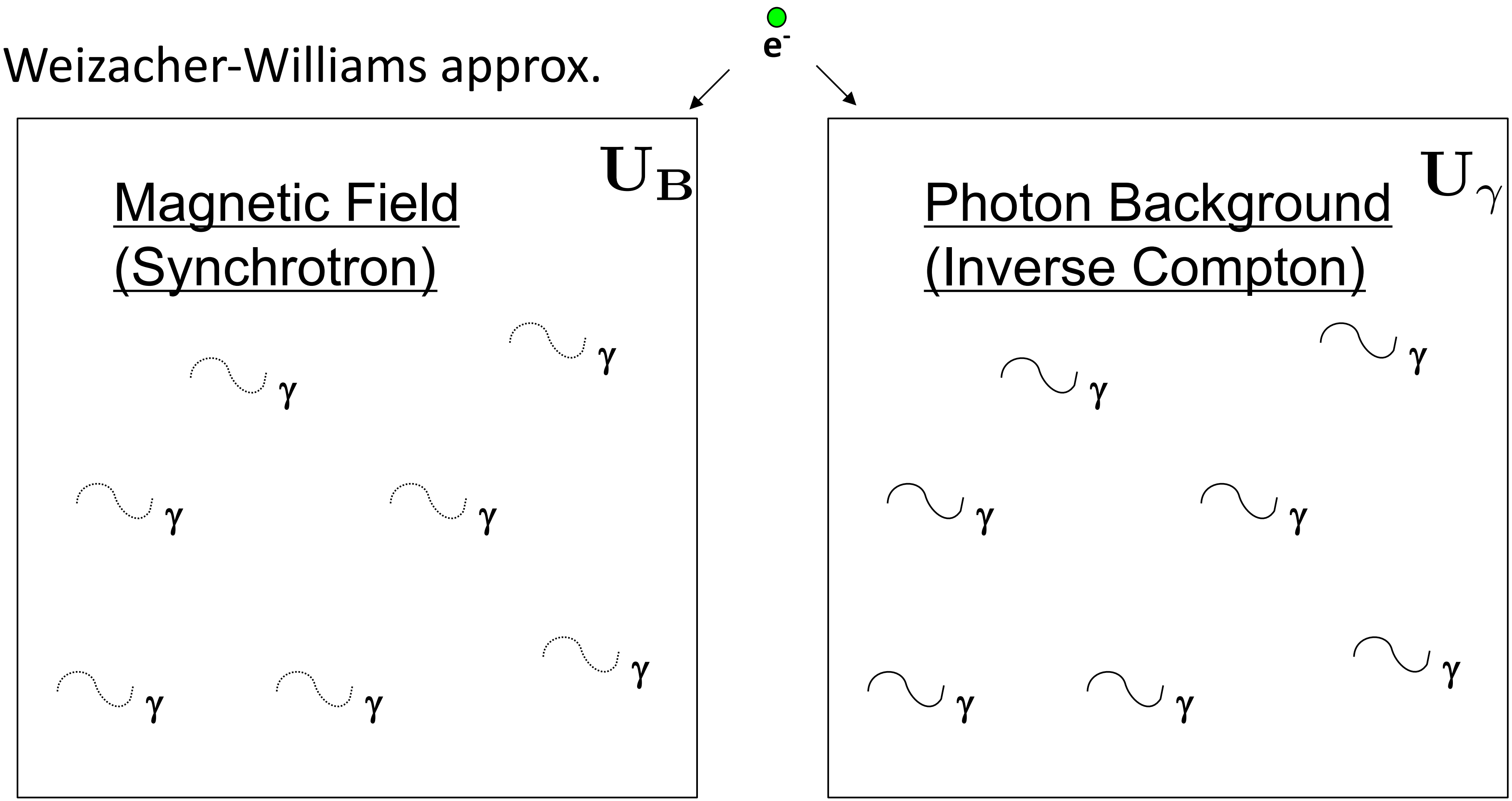

[HESS- C. Hoishen, A. Taylor, et al., Nature 2019]

$$\frac{\mathbf{dN}}{\mathbf{dE}_\gamma} \propto \mathbf{E}_\gamma^{-\Gamma}$$

- H.E.S.S. flux (100 - 440 GeV). Photon index consistent with -2.0.
- Fermi-LAT (detection < 700 s). Photon index -2.0.
- XRT Photon index is -2.0.
- X-ray, HE + VHE Gamma-ray energy fluxes all sit at a consistent level.
- Afterglow falling at same rate in all high energy wavelengths.

# Possible VHE Emission Processes

Weizacher-Williams approx.



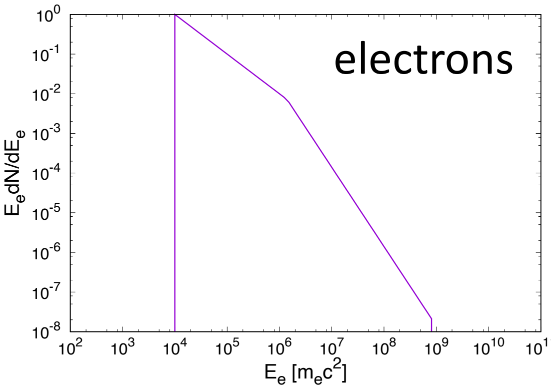

Virtual Photons

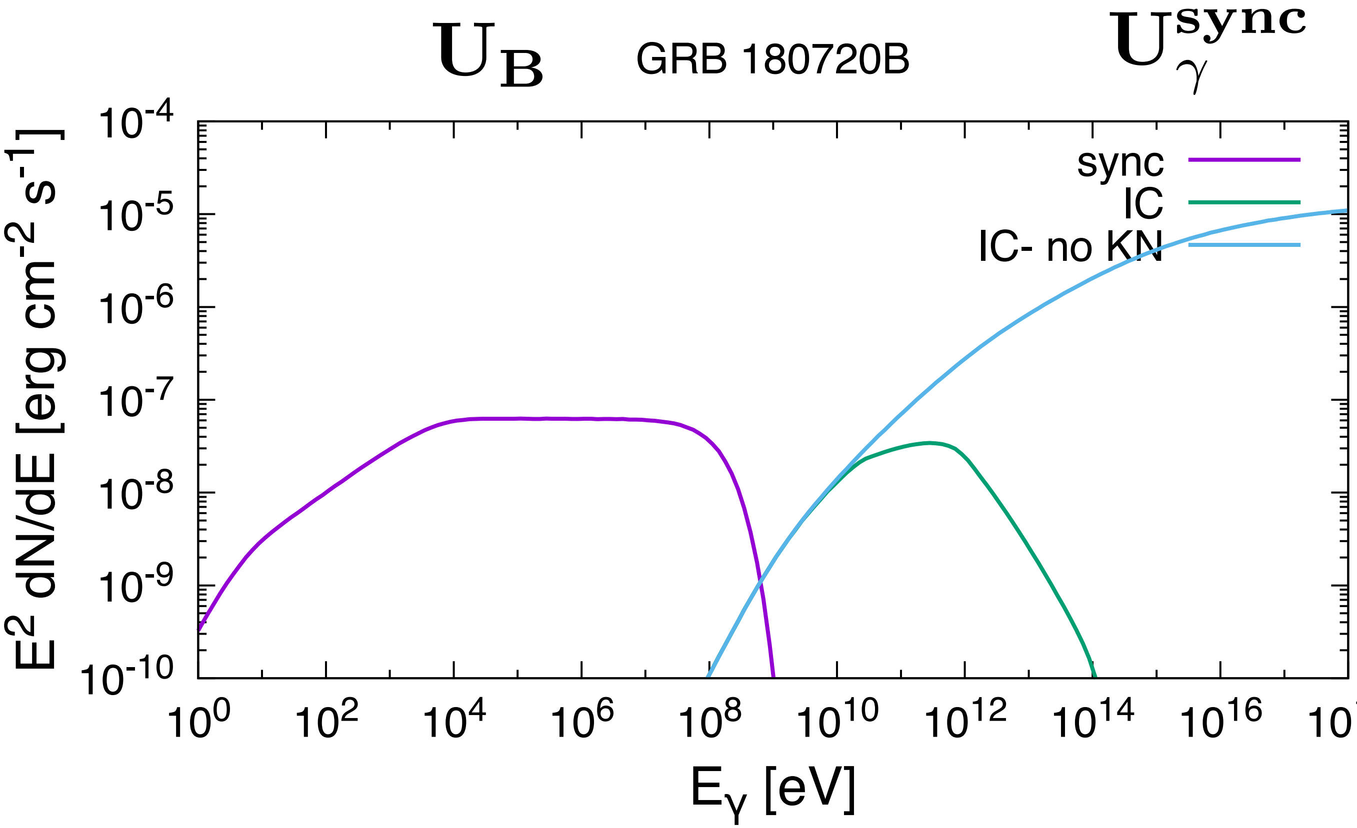
$$E_\gamma^{target} = \left(\frac{B}{B_{crit}}\right) m_e c^2$$

Real Photons

$$E_\gamma^{target}$$

# GRB 180720B SED- SSC Model Fit



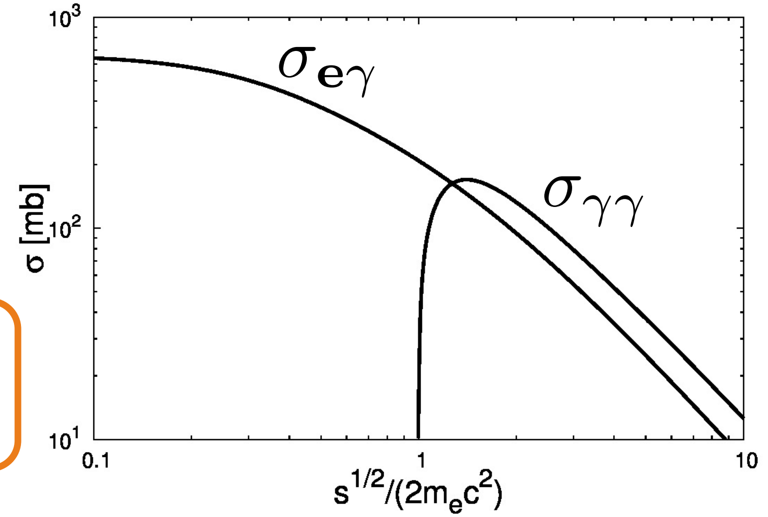



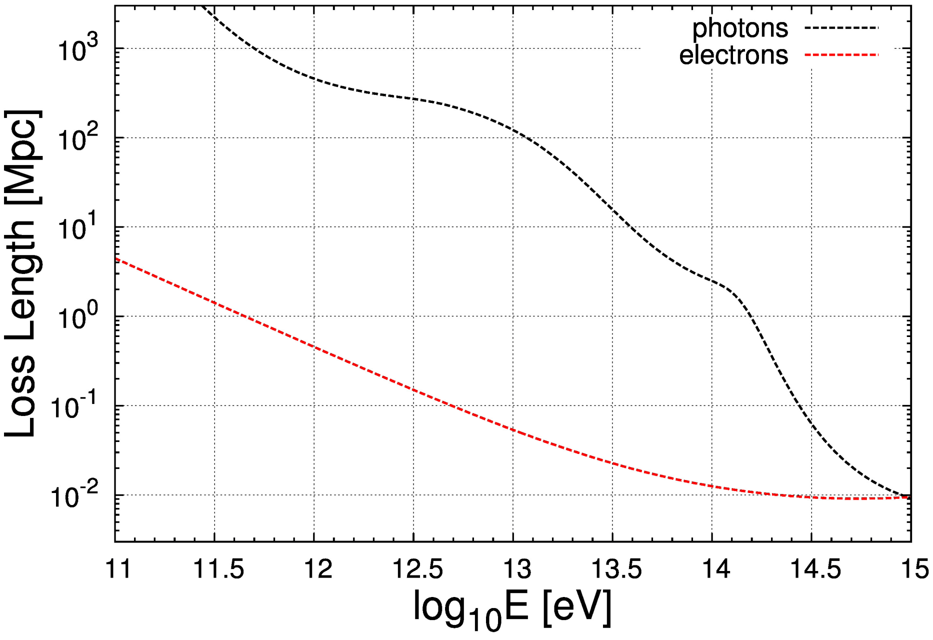

Without KN effects, the ratio of the heights of the IC to Synchrotron bumps would scale with $U_e/U_B$ (ie. $\varepsilon_e/\varepsilon_B$)

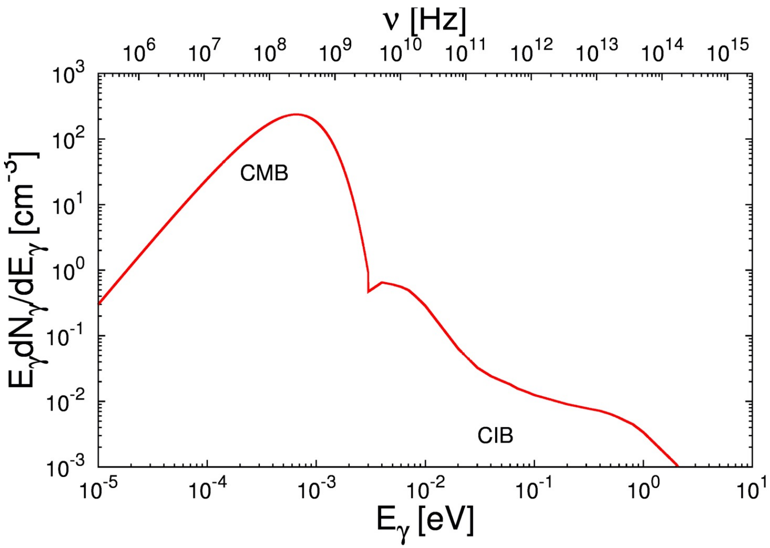
However, an SSC Origin of the Emission has been that adopted by others to describe early time VHE emission [Nature 575, 459-463 (2019)]

# Energy Loss Rates of Electrons and Photons

$$\mathbf{R} = \frac{\mathbf{m_e^2 c^4}}{\mathbf{2E_e^2}} \int_0^\infty \mathbf{d}\epsilon_\gamma \frac{\mathbf{1}}{\epsilon_\gamma^{\mathbf{2}}} \frac{\mathbf{dn}}{\mathbf{d}\epsilon_\gamma} \mathbf{K_e} \int_0^{\mathbf{2E_e}\epsilon_\gamma/(\mathbf{m_e c^2})} \mathbf{d}\epsilon'_\gamma \epsilon'_\gamma \sigma(\epsilon'_\gamma)$$

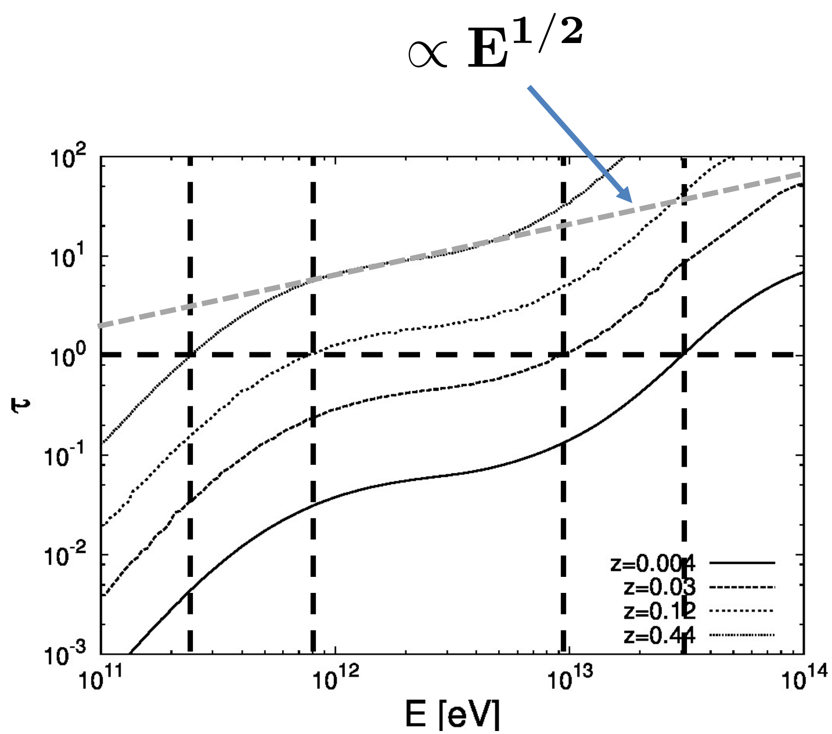


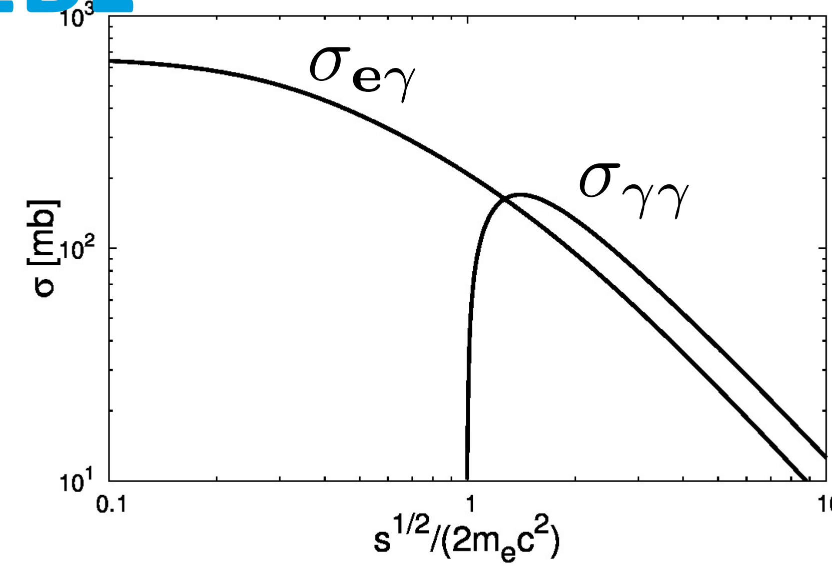



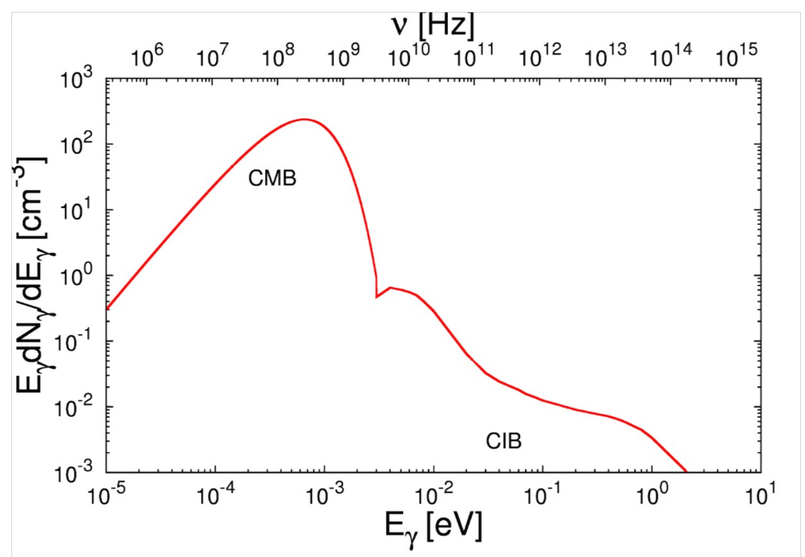




DESY.

# Attenuation through Pair Production on the EBL



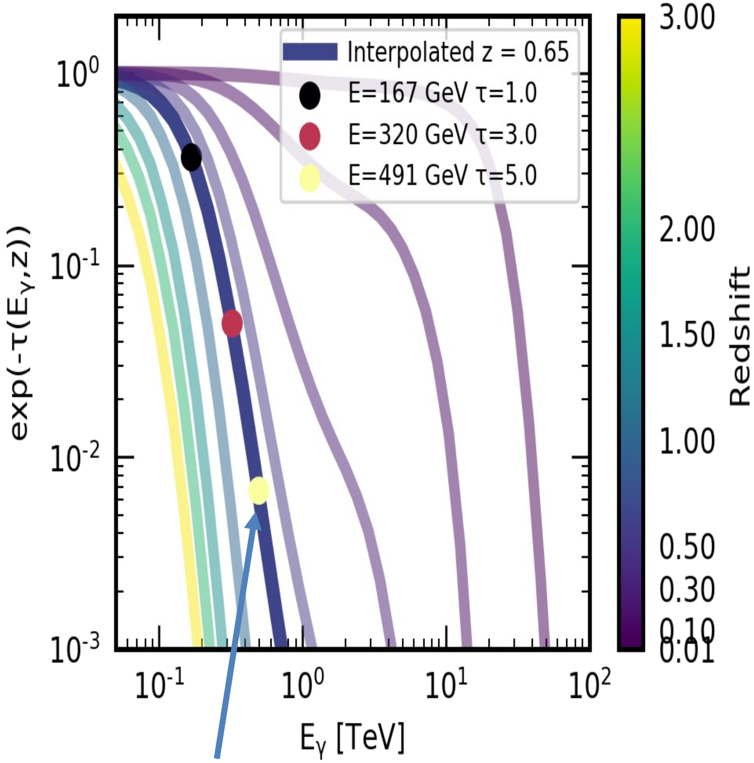



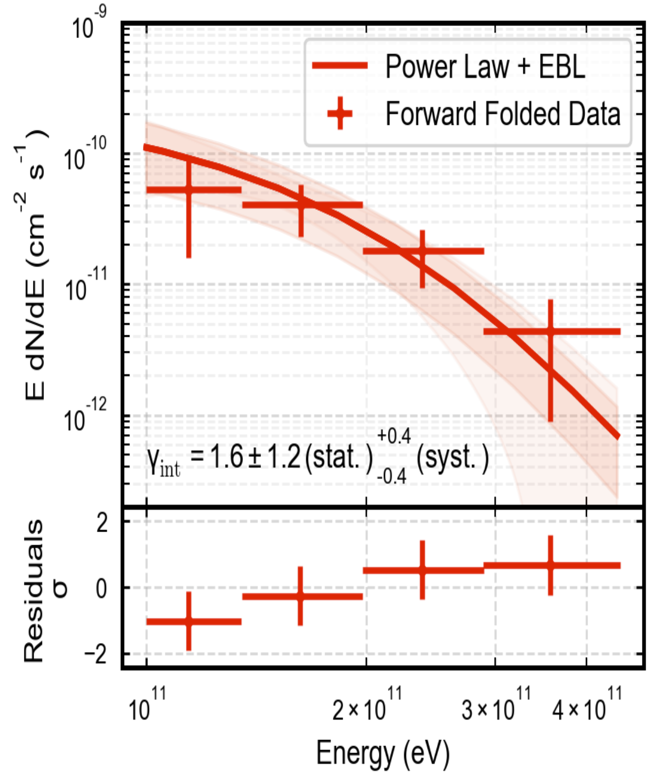
# GRB 180720B H.E.S.S. Detection

Very hard intrinsic spectrum (EBL de-absorbed), $\frac{dN}{dE} = \Phi_0 \left(\frac{E}{E_0}\right)^{-\gamma_{int}} \times exp(-\tau(E,z))$

redshift 0.65 (most distant GRB from the 3 detected at VHE)

[HESS- C. Hoishen, A. Taylor, et al., Nature 2019]

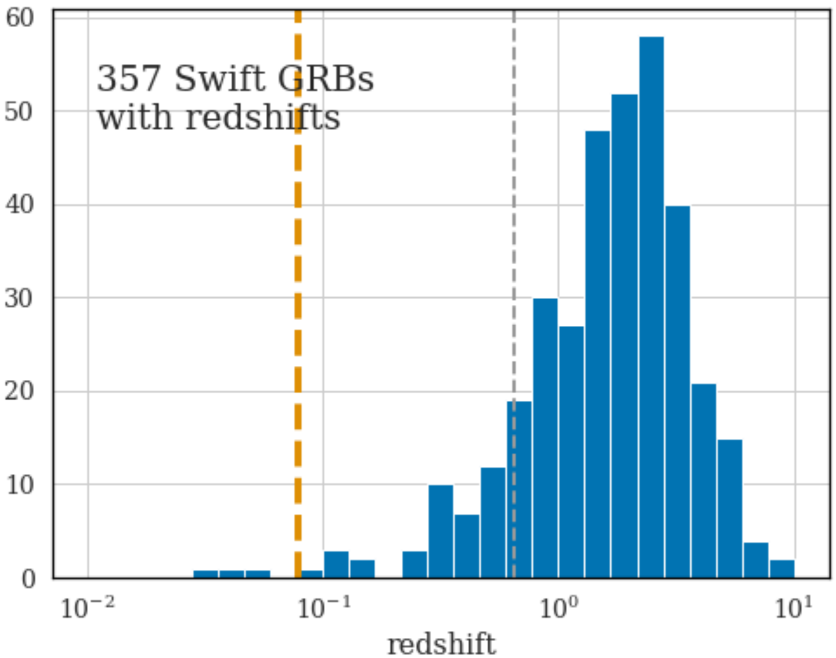


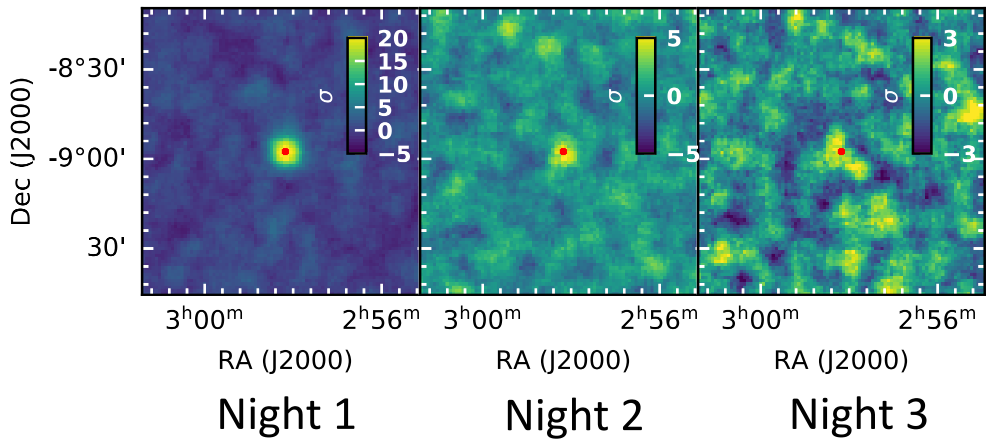




98% absorption at ~500 GeV due to EBL

# HESS Detection of GRB 190829A

First detection of a GRB in VHE band for multiple nights

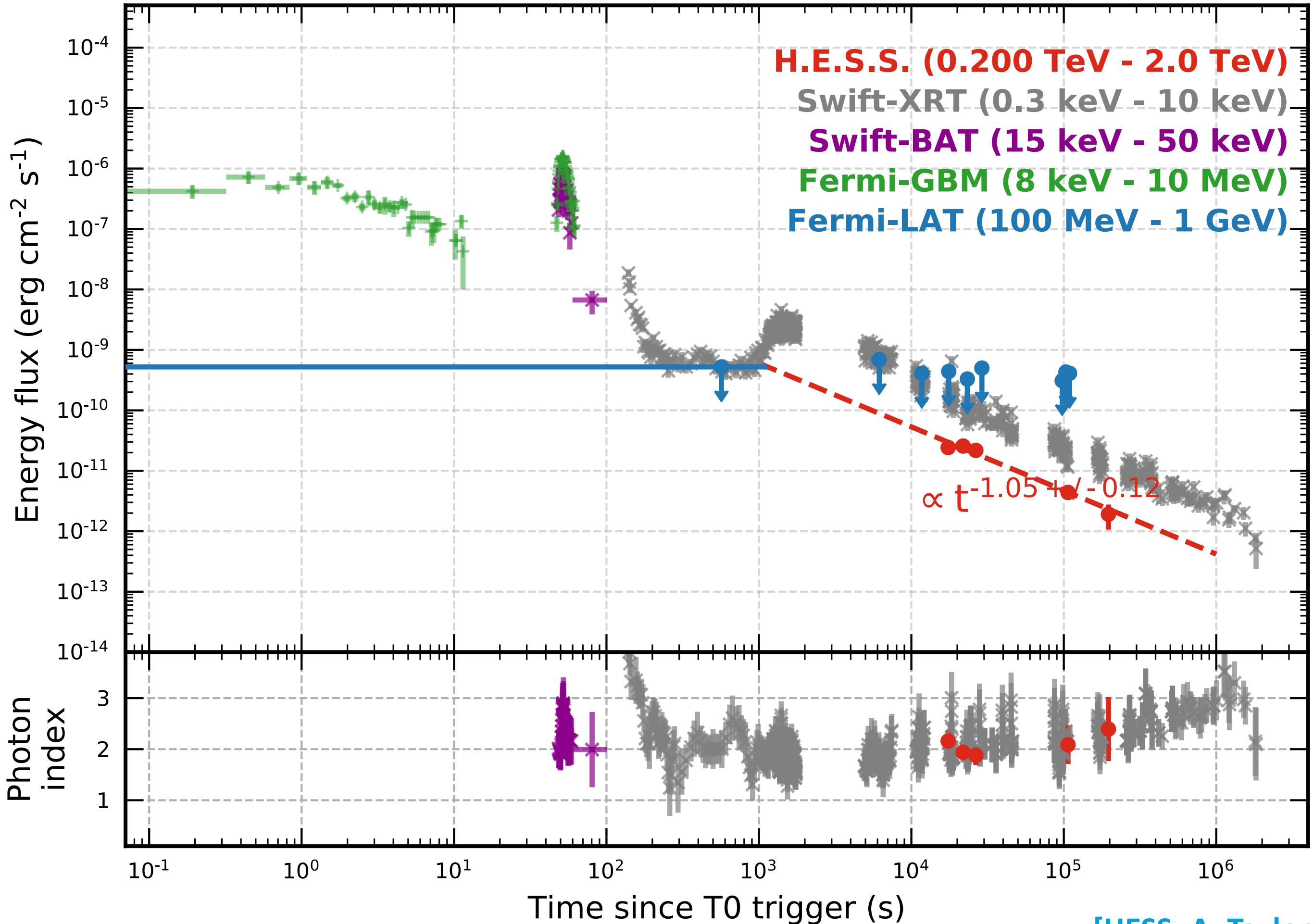



[HESS- A. Taylor, et al., Science 2021]

$t^{GBM}_{90}$ ~ 60 s, $t^{BAT}_{90}$ ~ 60 s
z = 0.078

# MWL Energy Flux Lightcurve




GRB was not detected by Fermi-LAT

[HESS- A. Taylor, et al., Science 2021]

X-ray and Gamma-ray energy fluxes decay in a remarkably similar way-

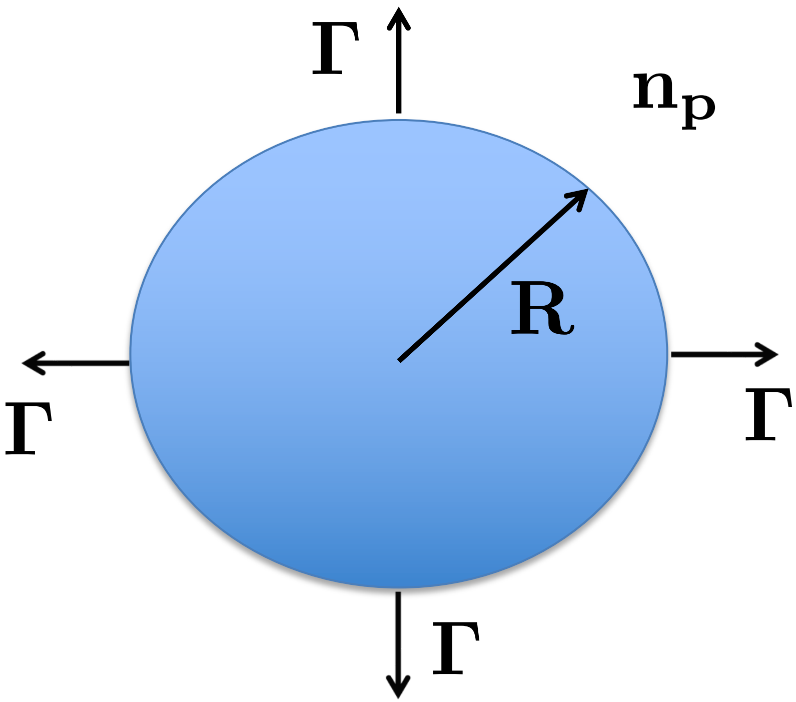
$$\mathbf{F(t) \propto t^{-\alpha}}$$

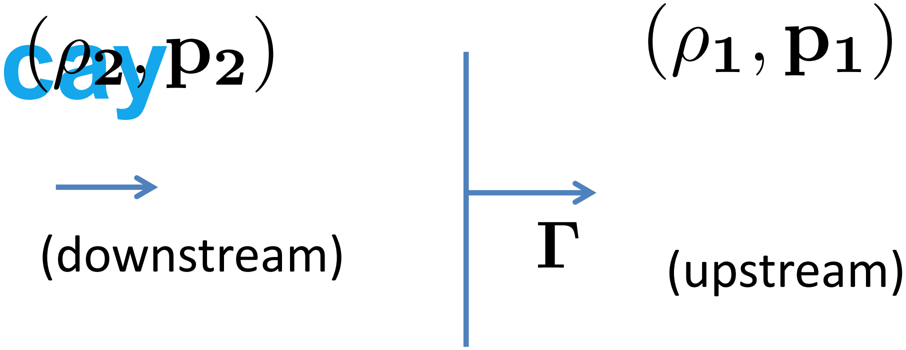
$$\alpha_{\mathrm{XRT}} = \mathbf{1.09 \pm 0.04}$$

$$\alpha_{\mathrm{HESS}} = \mathbf{1.05 \pm 0.12}$$

DESY.

# Origin of Synchrotron Temporal Decay



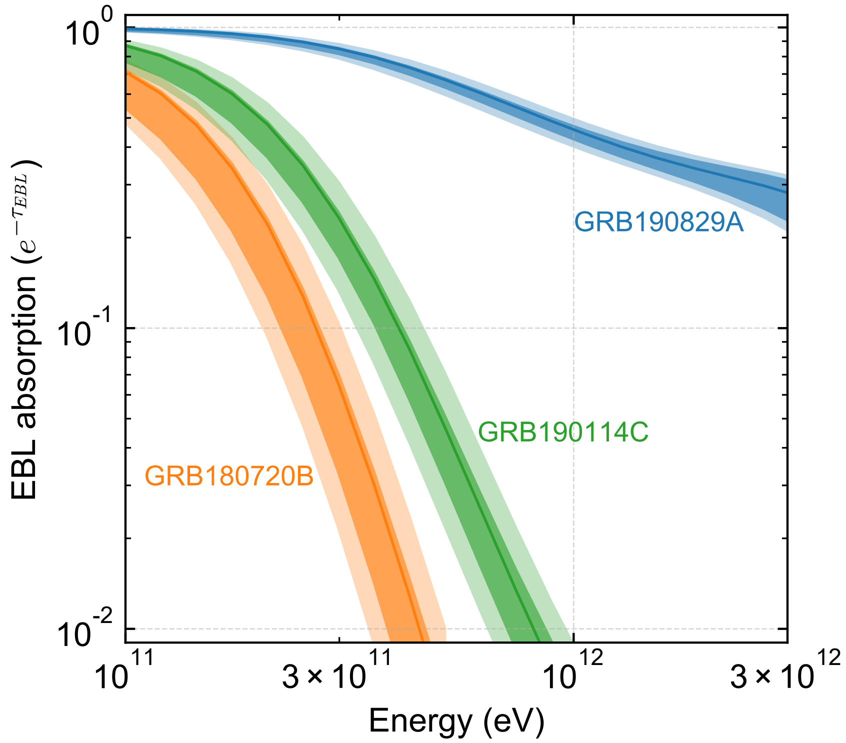




$$\frac{L^{iso}_{sync}}{4\pi\Gamma^2R^2c} = \eta_\gamma \Gamma^2 n_p m_p c^2$$

$$\Gamma \propto t^{-3/8} \qquad R \propto t^{1/4}$$

$$L^{iso}_{sync} \propto t^{-1}$$

# Energy Spectrum Information



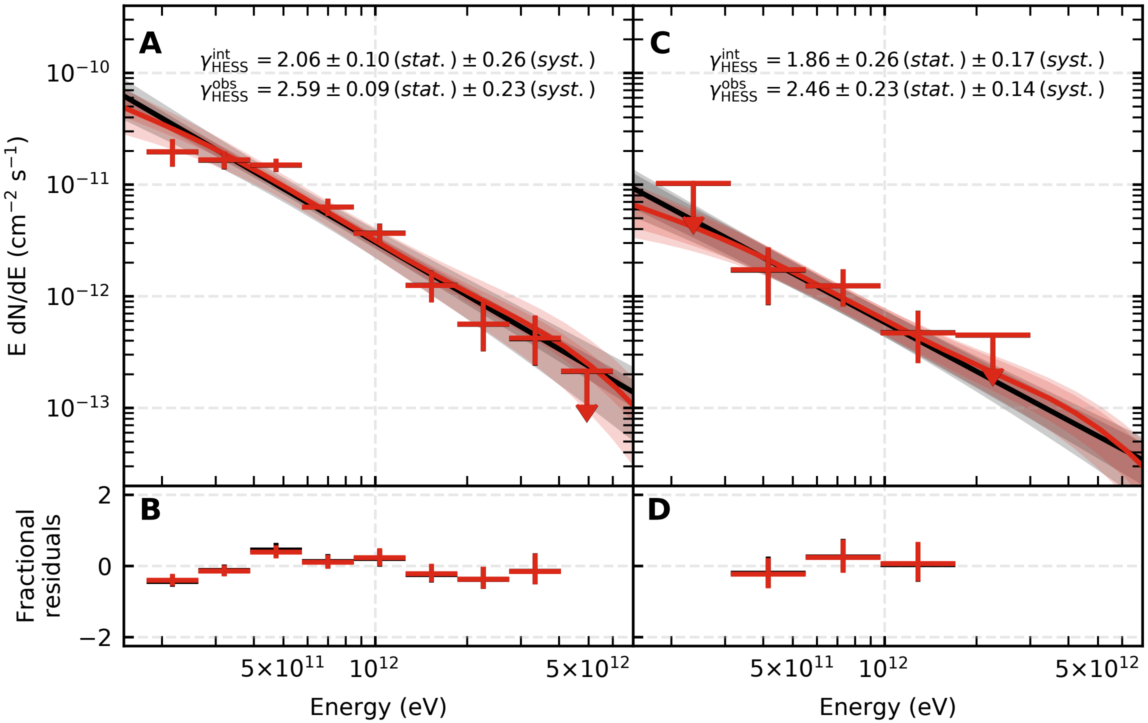

The effect of the EBL on the (optically thin) attenuation for a nearby (z=0.08) source for $E_\gamma$<6 TeV is a softening of the spectrum by around $\Delta\Gamma\approx0.5$, starting around 250 GeV.

[HESS- A. Taylor, et al., Science 2021]

# Spectra- First 2 Nights

Note- decided to adopt gammapy for these results (ie. open source) tool results

$$\mathbf{F(E) = N \left(\frac{E}{E_0}\right)^{-\gamma_{int}} e^{-\tau}}$$




X-ray and Gamma-ray spectral indexes are remarkably similar

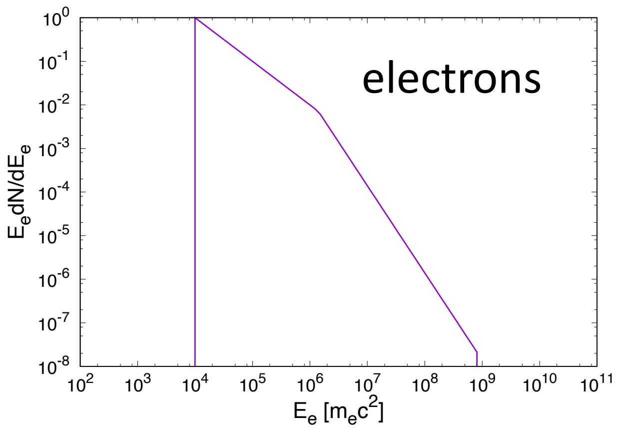
[HESS- A. Taylor, et al., Science 2021]

$$\gamma_{\mathrm{HESS}}^{\mathrm{1st}} = \mathbf{2.06 \pm 0.10} \qquad \gamma_{\mathrm{XRT}}^{\mathrm{1st}} = \mathbf{2.03 \pm 0.06}$$

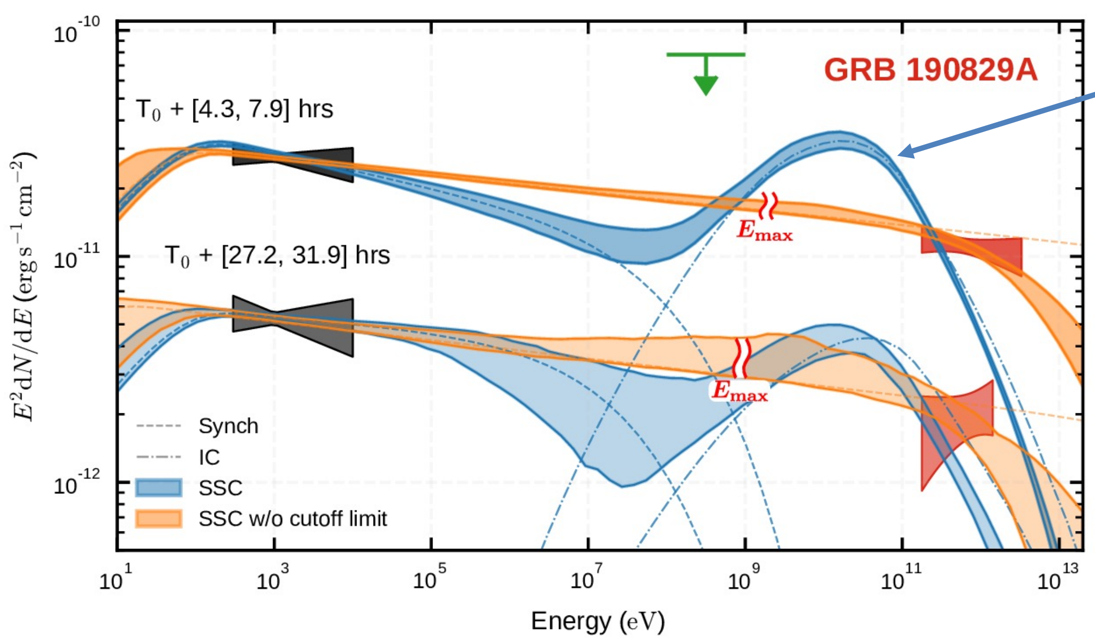
$$\gamma_{\mathrm{HESS}}^{\mathrm{2nd}} = \mathbf{1.86 \pm 0.26} \qquad \gamma_{\mathrm{XRT}}^{\mathrm{2nd}} = \mathbf{2.04 \pm 0.10}$$

DESY.

# GRB 190829A- Testing the "Standard" and Non-Standard VHE Emission Scenarios




MCMC fits to Night 1



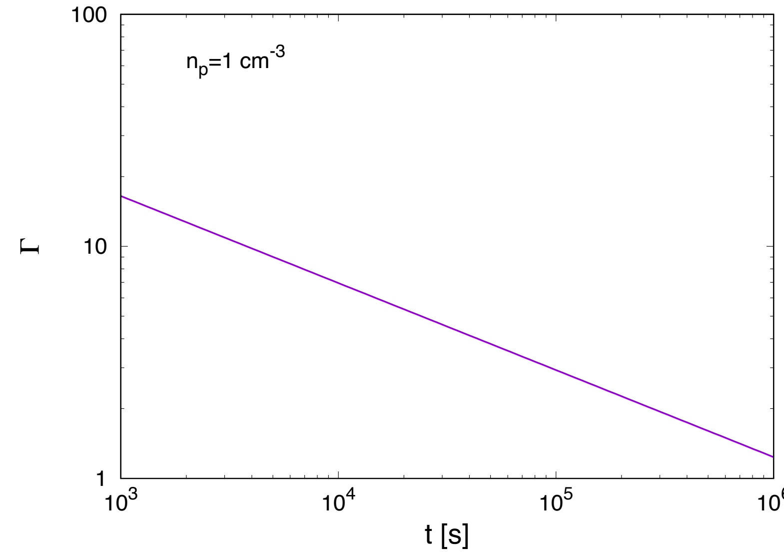

Synchrotron + SSC
$\mathbf{E_e > 400\ GeV}$

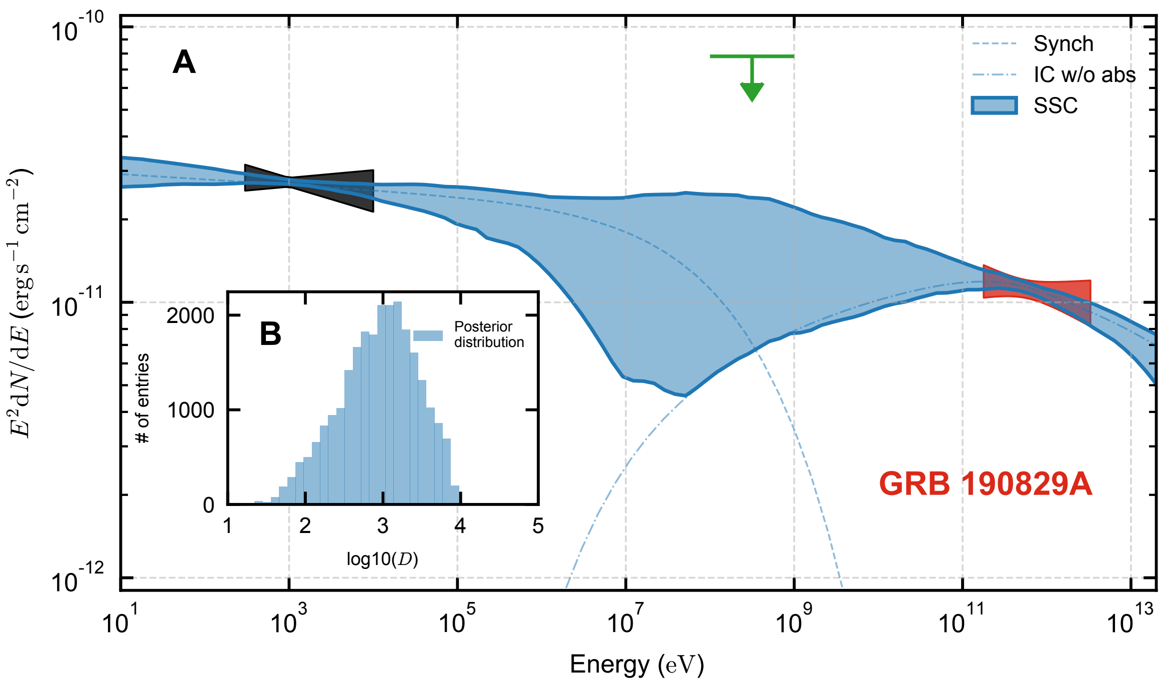
Synchrotron Only
$\mathbf{E_e > 1}$ PeV

[HESS- A. Taylor, et al., Science 2021]

# Saving the One Zone SSC Paradigm

$$\Gamma = 6\left(\frac{E_{51}}{n_0 t_{4hrs}^3}\right)^{1/8}$$




[HESS- A. Taylor, et al., Science 2021]

# Recently Proposed Ways to Resolve to Go Beyond the One Zone SSC Scenario

- External inverse Compton scattering? (B. Zhang et al. 2020)
- Convertor mechanism is taking place? (E. Derishev et al. 2019)
- Two zone synchrotron emission is taking place? (D. Khangulyan et al. 2021)
- Reverse shock contaminates X-ray emission? (O.S. Salafia et al. 2021)

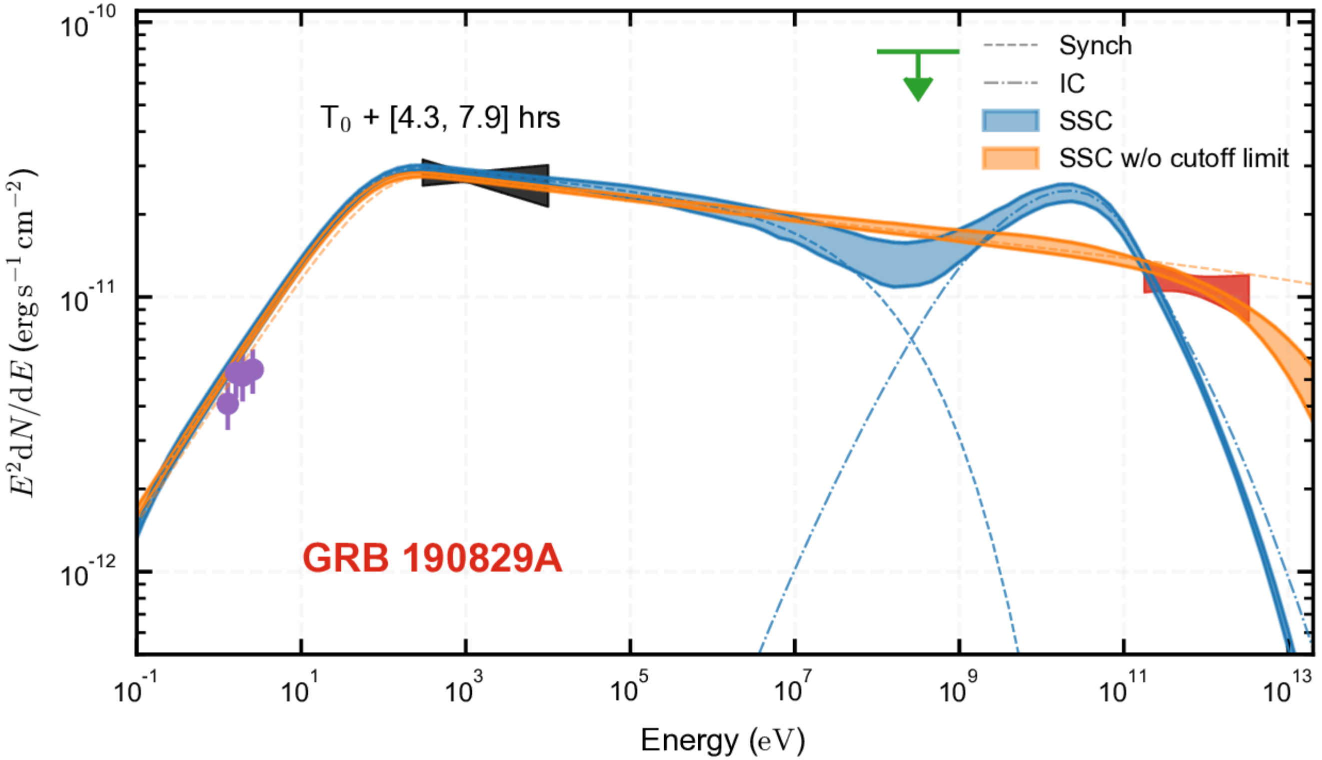
……a renaissance of GRB astrophysics seems to be starting following the TeV gamma-ray detections

# Conclusions

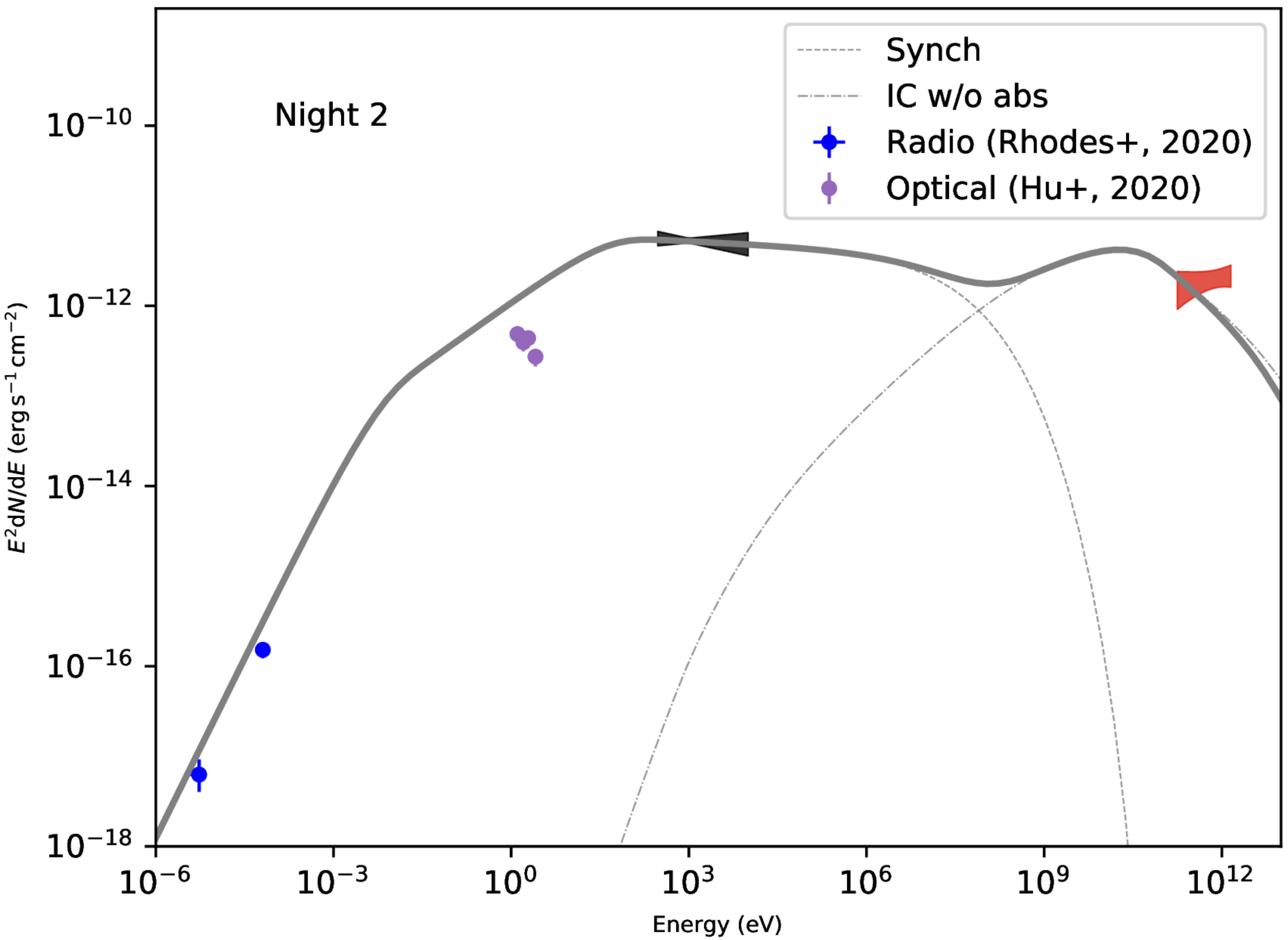
- Fast shocks from massive energy release events are the most viable sources of extragalactic cosmic rays
- Synchrotron emission from long GRB tell us directly how efficient these sources operate as cosmic ray accelerators
- We are finally starting to probe the very high energy (TeV) gamma-ray emission from GRB, allowing us to start probing the magnetic fields in the source
- Curiously, the most recent HESS GRB detection is compatible with a continuation of the synchrotron emission beyond the expected supposed theoretical limit

*"Experimental confirmation of a prediction is merely a measurement. An experiment disproving a prediction is a discovery."* – E. Fermi

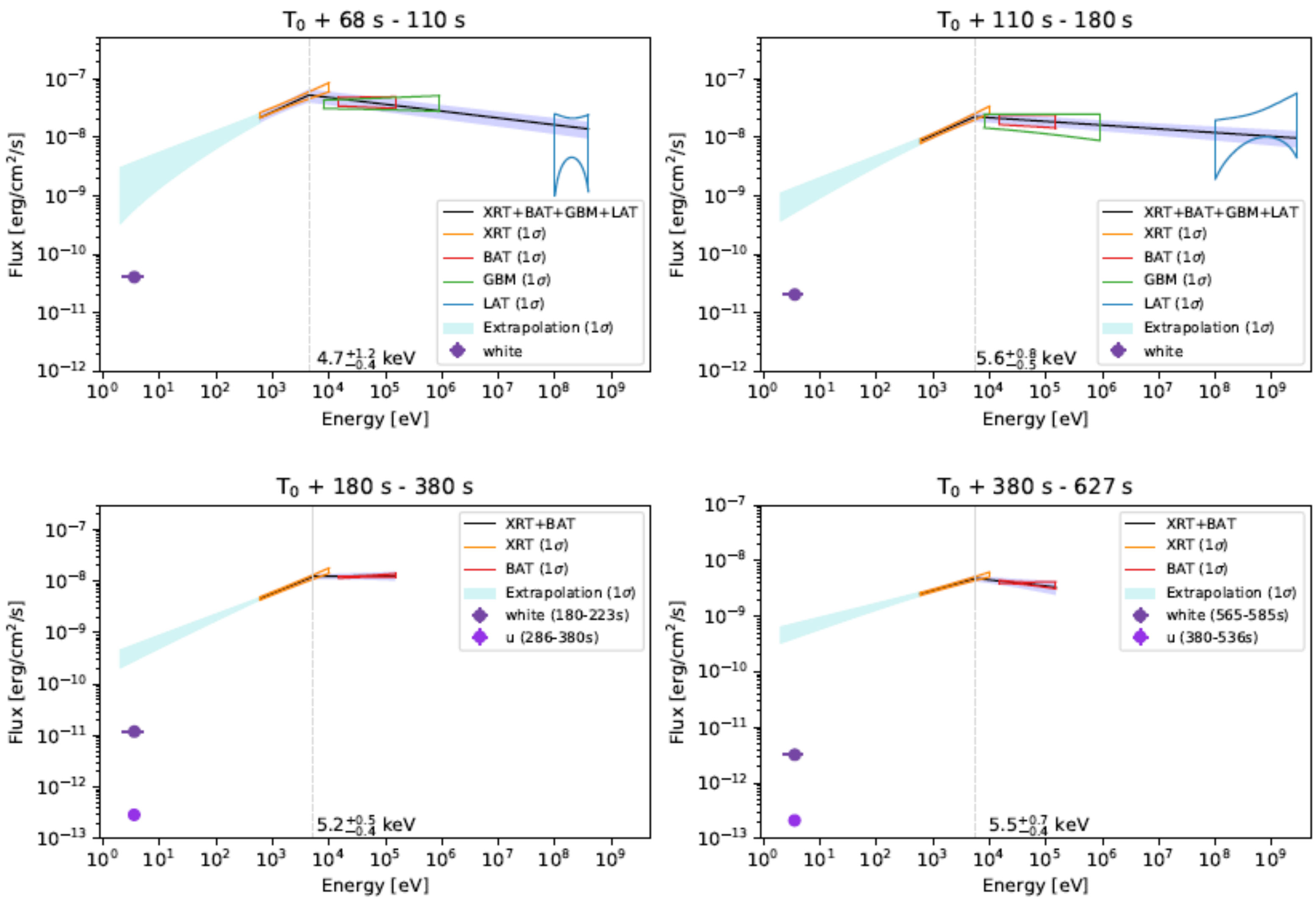
# GRB 190829A- Optical Data



# GRB 190829A- Radio Data

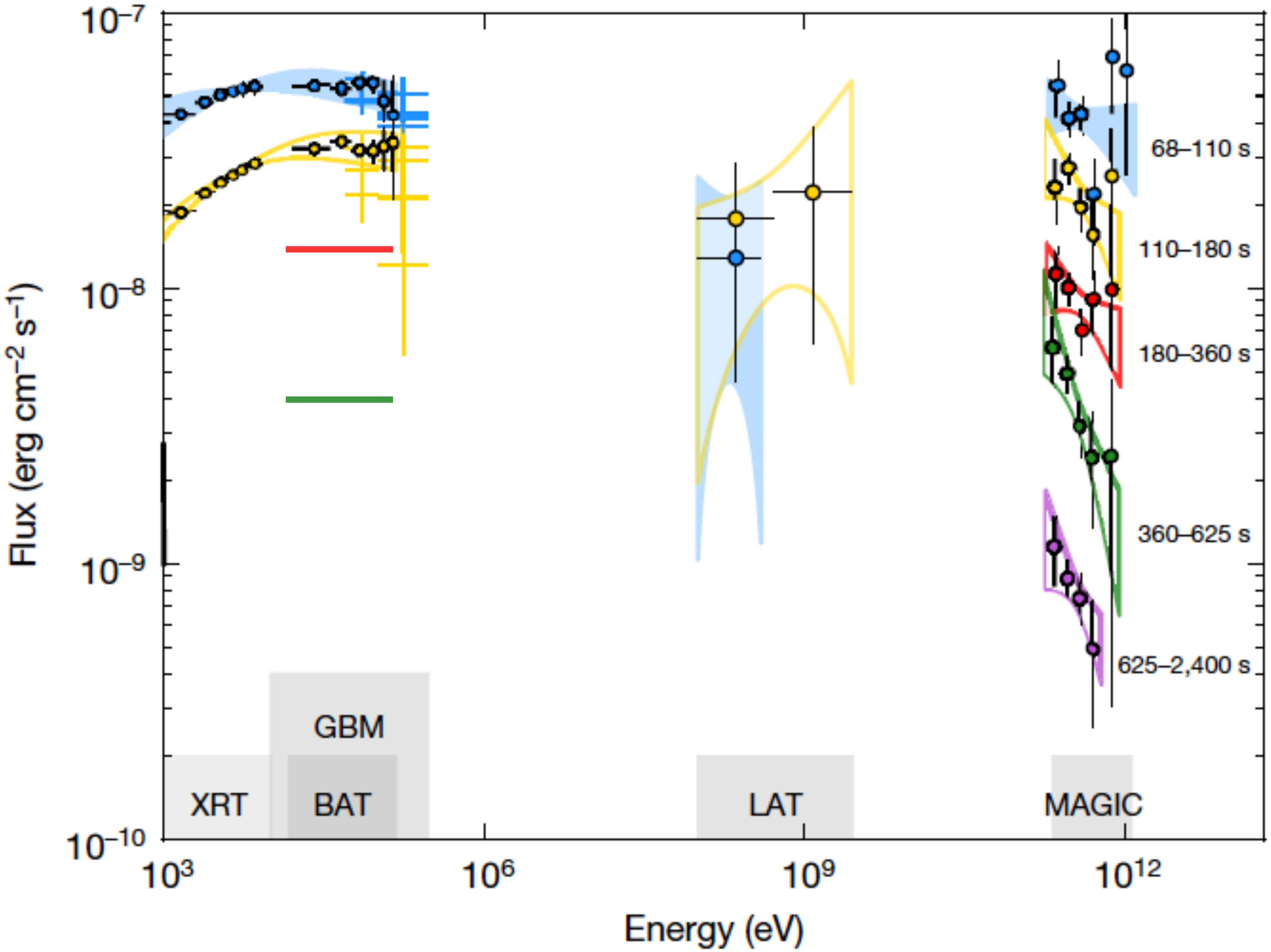


# GRB 190114C



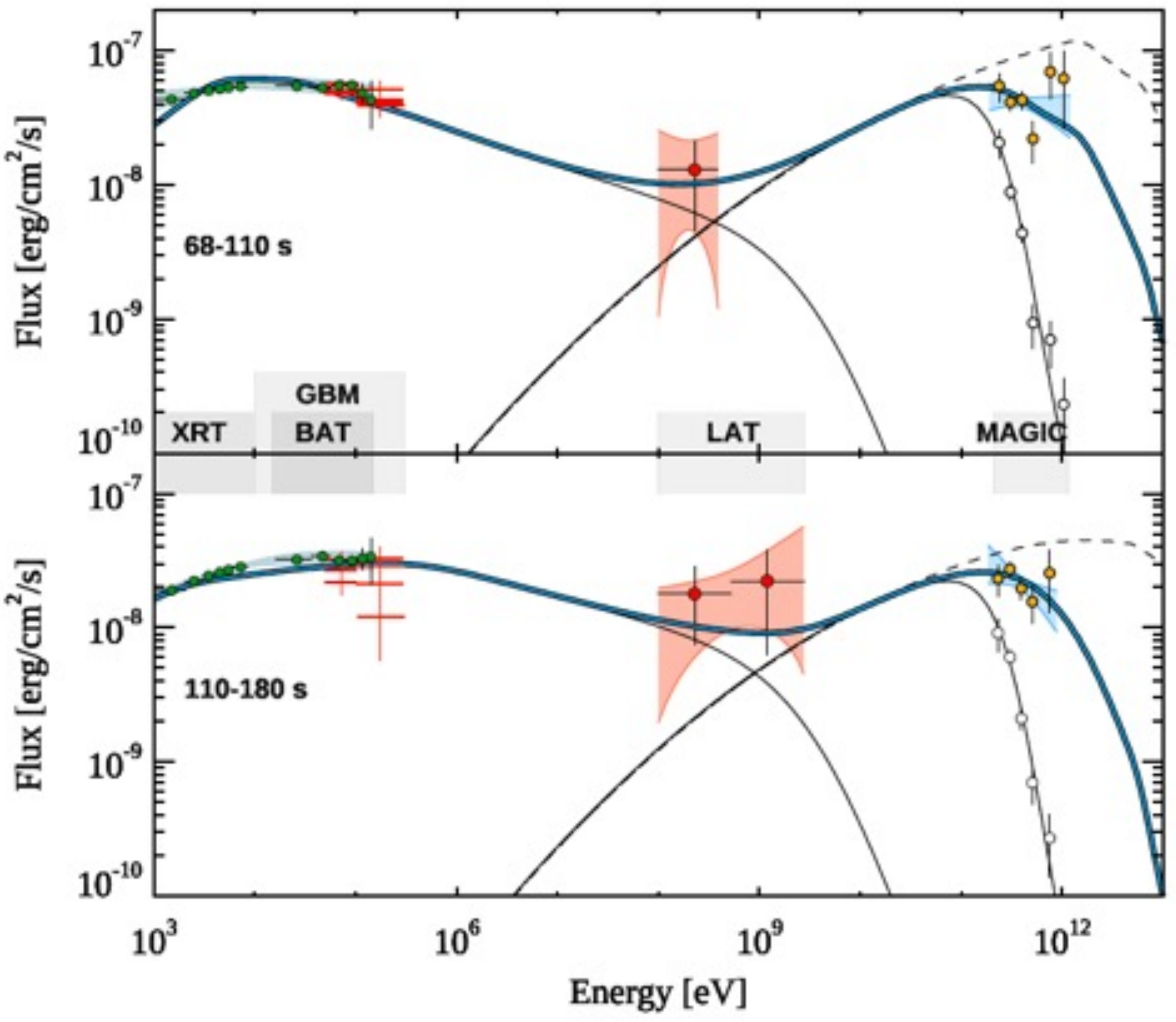
T0 + 68 s - 110 s
T0 + 110 s - 180 s
T0 + 180 s - 380 s
T0 + 380 s - 627 s
Flux [erg/cm2/s]
Energy [eV]
XRT+BAT+GBM+LAT
XRT+BAT
XRT (1σ)
BAT (1σ)
GBM (1σ)
LAT (1σ)
Extrapolation (1σ)
white
white (180-223s)
u (286-380s)
white (565-585s)
u (380-536s)
4.7+1.2−0.4 keV
5.6+0.8−0.5 keV
5.2+0.5−0.4 keV
5.5+0.7−0.4 keV

# GRB 190114C



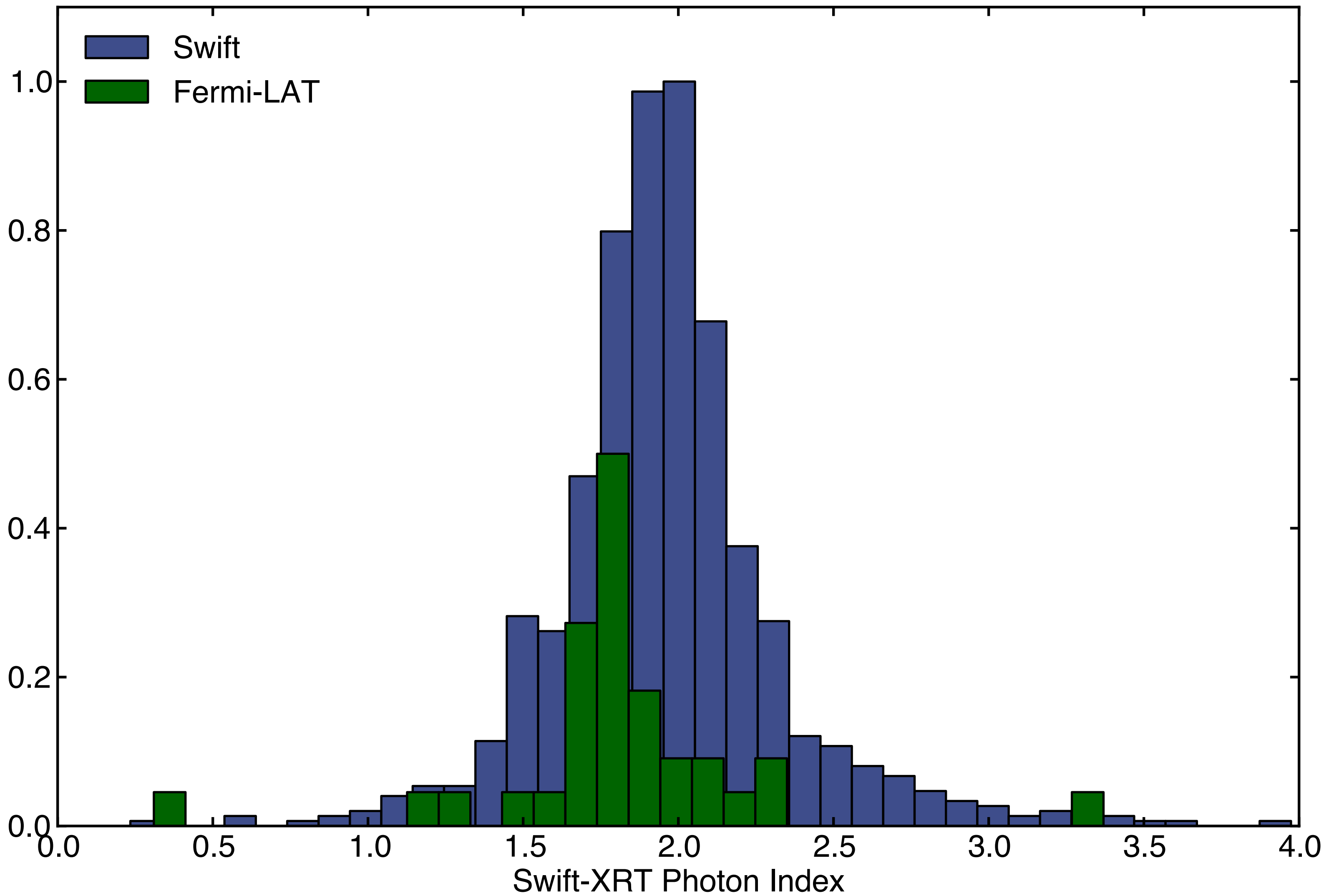

DESY.

# GRB 190114C



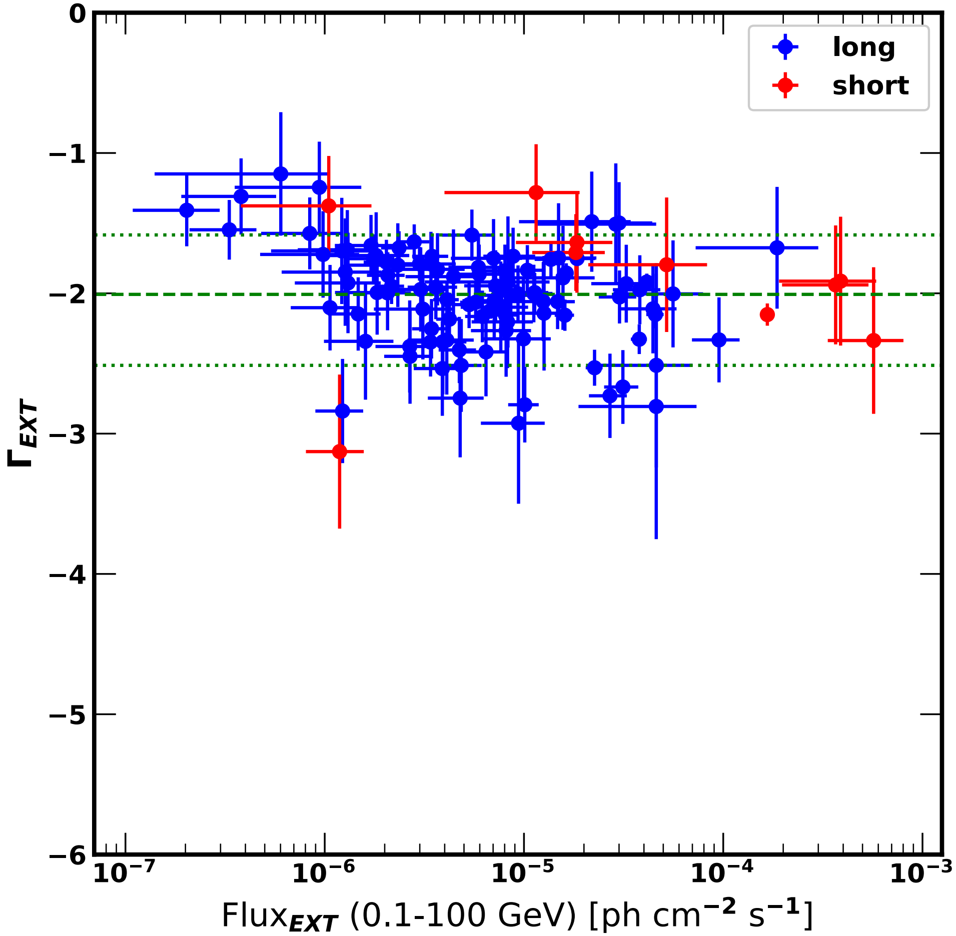

DESY.

# Swift XRT Photon Index Distribution



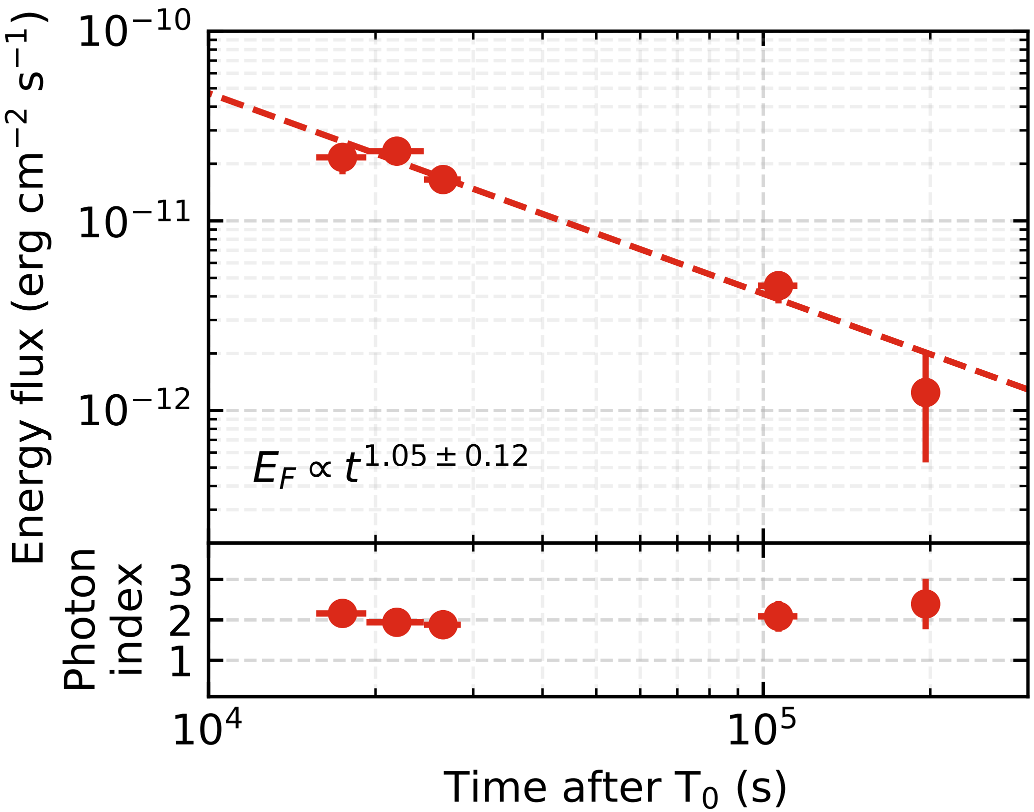

[Ajello et al., Ap. J., 863 138, 2018]

# Fermi-LAT Photon Index Distribution




[Ajello et al., Ap. J., 878:52, 2019]

# Lightcurve- 3 Day Temporal Decay

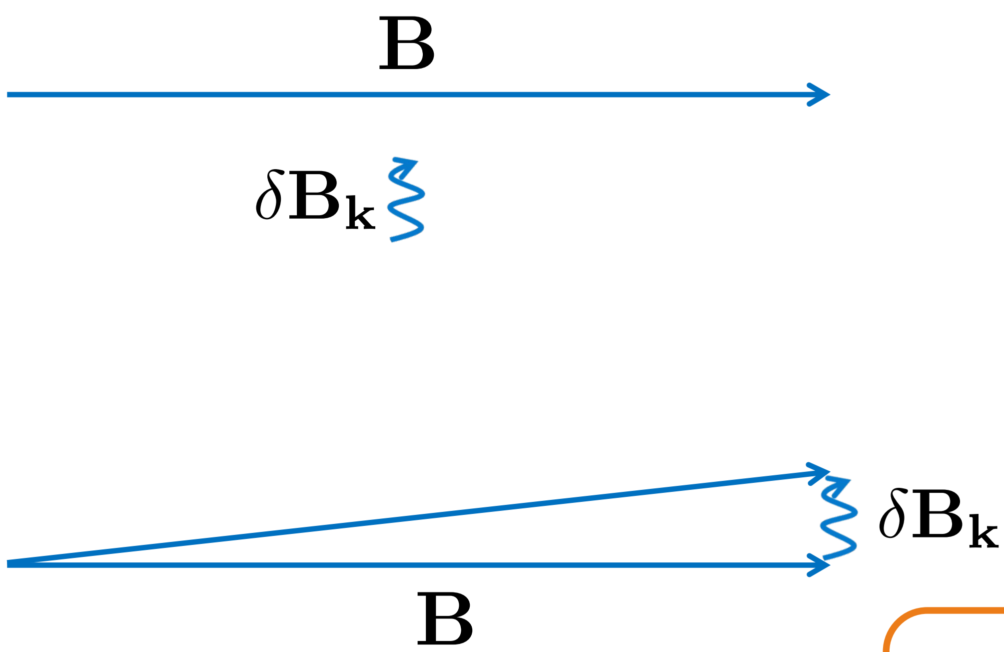



$$\mathbf{F(t) = F_0 \left(\frac{t}{t_0}\right)^{-1}}$$

$$\text{Fluence} = \int_{\mathbf{t}_{\min}}^{\mathbf{t}_{\max}} \mathbf{F(t)dt} = \mathbf{F_0 t_0} \ln(\mathbf{t}_{\max}/\mathbf{t}_{\min})$$

# Particle Diffusion in Magnetic Turbulence (Quasi-Linear Theory)?

The propagation of cosmic rays is dictated by the magnetic field landscape they live in.




$$\delta\theta = \frac{\delta \mathbf{B_k}}{\mathbf{B}}$$

$$\langle \Delta\theta^2 \rangle = \mathbf{N}\langle \delta\theta^2 \rangle = \left(\frac{\mathbf{t}}{\mathbf{t_{lar}}}\right)\langle \delta\theta^2 \rangle$$

$$\mathbf{D}_{\theta\theta} = \frac{\Delta\theta^2}{\mathbf{t}} = \frac{1}{\mathbf{t_{lar}}}\left(\frac{\delta \mathbf{B_k^2}}{\mathbf{B^2}}\right)$$

DESY.

# Spatial Diffusion in Magnetic Turbulence?

$$\mathbf{t_{scat}} \approx \frac{\mathbf{1}}{\mathbf{D}_{\theta\theta}}$$

$$\frac{\mathbf{D_{xx}}}{\mathbf{c}} \approx \mathbf{t_{scat}}$$

$$\frac{\mathbf{D_{xx}}}{\mathbf{c}} \approx \mathbf{t_{lar}} \left( \frac{\mathbf{B^2}}{\delta \mathbf{B_k^2}} \right)$$